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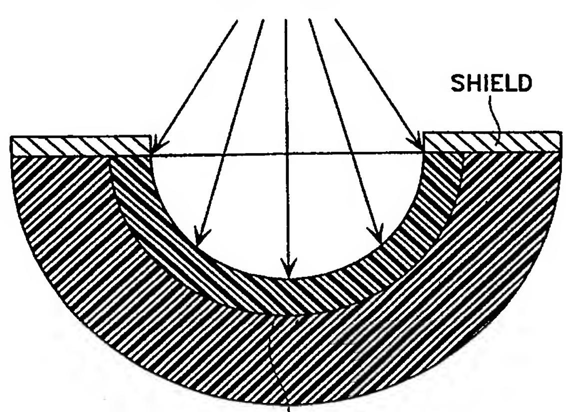
(57) Abstract

This invention is a method for improving the wear resistance of an implant, made of polyethylene by cross-linking its bearing surface layer, while leaving its non-bearing interior uncross-linked. Such cross-linking may be achieved by electron beam irradiation or by chemical cross-linking of the implant or the polyethylene from which the implant is made. The resulting implant or polyethylene may be further treated to remove the residual free radicals (generated by the electron beam cross-linking process); to remove residual chemicals (generated by the chemical cross-linking process): to remove its most oxidized layer; to stabilize its size and shape; to improve, by remelting its oxidation resistance; and/or to reshape it into the final implant. Also presented are the resulting implant, and polyethylene.



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WEAR RESISTANT SURFACE-GRADIENT CROSSLINKED POLYETHYLENE

This application is a continuation-in-part of a United State patent application, serial number 09/060,387, entitled "Wear Resistant Surface-Gradient Crosslinked Polyethylene", of Harry A. McKellop, et al., filed on April 14, 1998, which in turn is a continuation-in-part of a Patent Cooperation Treaty patent application, international application number PCT/US97/18758, of the same title and inventors, filed on October 14, 1997, which in turn was based on a United States provisional application serial number 60/028,355 entitled "Wear-Resistant Polymer", of Harry A. McKellop, et al., filed on October 15, 1996.

TECHNICAL FIELD OF THE INVENTION

The present invention is in the field of medical implants made of polyethylene (PE), in particular, ultrahigh molecular weight PE (UHMWPE) and high molecular weight PE (HMWPE).

BACKGROUND OF THE INVENTION

Ultrahigh molecular weight polyethylene (hereinafter referred to as "UHMWPE") is commonly used to make prosthetic joints such as artificial hip joints. Wear of acetabular cups of UHMWPE in artificial joints introduces many microscopic wear particles into the surrounding tissues. The reaction to these particles includes inflammation and deterioration of the tissues, particularly the bone to which the prosthesis is anchored. Eventually, the prosthesis becomes painfully loose and must be replaced. It is generally accepted by orthopaedic surgeons and biomaterials scientists that the reaction of tissue to wear debris is the chief cause of long-term failure of such prostheses.

The literature describes numerous attempts to improve the wear resistance of polyethylene (hereinafter referred to as "PE") in joint replacements. Grobbelaar et al.[*J. Bone & Joint Surgery*, **60-B(3):** 370-374 (1978)] attempted to improve the cold-flow characteristics of "high-density" PE prostheses made of Hostalen RCH 1000 C, without sacrificing its low-frictional properties, through a process of radiation crosslinking. Grobbelaar et al., crosslinked the PE using gamma radiation in the presence of crosslinking gases, including acetylene and chlorotrifluoroethylene, or in an inert nitrogen atmosphere. Due to the absorption of the crosslinking gasses, the surface was more crosslinked than the interior of the PE. Nevertheless, because of the high penetration power of gamma radiation, the PE became crosslinked throughout.

To improve the wear resistance of a medical prosthetic device, Farrar, WO 95/21212, used plasma treatment to crosslink its wear surface. This wear surface comprises a plastic material such as UHMWPE. Crosslinking was assumed to have occurred based on the presence of Fourier transform infrared absorption bands at 2890 cm^{-1}. Farrar claims his ATR (attenuated total reflection) data imply that he had achieved a penetration depth of 0.5 microns, but the degree of crosslinking is not disclosed.

Streicher, *Beta-Gamma* 1/89: 34-43, used high penetration gamma radiation or high penetration (i.e., 10 MeV) electron beam radiation to crosslink UHMWPE and high molecular weight PE (hereinafter referred to as "HMWPE") specimens throughout their entire thickness. Streicher annealed the gamma irradiated material in a nitrogen atmosphere in order to increase crosslinking and reduce oxidation during long-term storage. Streicher found that the wear of the materials was <u>greater</u> after the crosslinking by electron beam radiation.

Higgins et al (Transactions of the 42nd Ann. Mtg., Orthopaedic Res. Soc., Feb. 19-22, 1996, p. 485) attempted to stabilize UHMWPE against oxidation after high penetration gamma irradiation (which crosslinked their specimens through

the entire thickness) by reducing the concentration of free radicals. They used the following post-irradiation treatments: (1) pressurizing in hydrogen at 15 psi for 2 hours, or (2) heating at 50°C for 182 hours. They compared the amount of free radicals remaining in the PE using electron spin resonance (ESR), but they did not assess the impact of these treatments on the mechanical or wear properties of the UHMWPE, nor on the oxidation resistance.

SUMMARY OF THE INVENTION

One aspect of the invention presents surface-gradient crosslinked (hereinafter also referred to as "surface-crosslinked") PE and medical implants (hereinafter abbreviated as "implants") having surface-crosslinked PE which are wear resistant. The PE is preferably UHMWPE or HMWPE. Non-limiting examples of the invention are acetabular cups made of surface-crosslinked PE, and surface-crosslinked PE tibial components of knee prostheses. The surface-crosslinked PE and implants may be made by the methods described below.

Another aspect of the invention presents a method for improving the wear resistance of the bearing surface of an implant. The implant or its bearing surface is made of surface-crosslinked PE, the PE is preferably UHMWPE or HMWPE. In one embodiment, the method comprises exposing the implant to an electron beam (the term "electron beam" is hereinafter referred to as "e-beam") radiation with an energy level specifically selected to crosslink the bearing surface of the implant, to improve the wear resistance, only to a depth sufficient such that the crosslinked layer will not be worn through during the life of the patient, while leaving the remainder uncrosslinked, thereby avoiding any reduction in mechanical properties that might otherwise result from crosslinking. Additionally, confining the crosslinking to a thin surface layer facilitates neutralizing residual free radicals caused by irradiation and/or extracting residual chemicals in the case of chemical

crosslinking, as described.

In another embodiment of the invention, instead of crosslinking the bearing surface with e-beam radiation, the bearing surface of the implant is crosslinked to a limited depth with a free radical generating chemical, again while leaving the remainder of the implant uncrosslinked for the reasons mentioned above. The free radical generating chemical is preferably a peroxide.

In both of the above methods, the crosslinking is preferably in the surface layer, gradually decreasing to nearly zero in the interior of the PE.

With e-beam crosslinking, it is preferable that the implant be packaged in a low oxygen atmosphere during irradiation, such as an inert gas (e.g., nitrogen) or a vacuum, in order to minimize oxidation and maximize crosslinking of the surface layer. However, if an implant is e-beam irradiated while in air, the outer layer of the bearing surface may then be removed, e.g., by machining, to eliminate the more oxidized and less crosslinked material. In such a case, the depth of crosslinking penetration of the e-beam can be increased by the appropriate amount to take into account the thickness of the material to be removed.

It is preferable that the surface-crosslinked material be treated to eliminate residual free radicals generated by the e-beam crosslinking process in order to stabilize it against long-term oxidation. This can be achieved by one or more of the following methods: (1) remelting the partially formed crosslinked material after crosslinking irradiation but prior to final shaping into the implant. In this case, either the surface destined to be the bearing surface of the implant is remelted, or the whole partially formed crosslinked material is remelted, (2) annealing the partially formed crosslinked material or the final shaped implant, (3) exposing the crosslinked material or implant to pressurized hydrogen and/or (4) treating the crosslinked material or implant using ethylene oxide.

With chemical crosslinking, the implant may be annealed after crosslinking to stabilize its size and shape and/or

the implant may be soaked in suitable solvent(s) to extract from the crosslinked surface layer any residual chemicals, resulting from decomposition of the free radical generating chemical, in order to minimize leaching out of such chemicals during *in vivo* use, and to minimize long-term oxidation of the crosslinked material. The soaking step may be conducted either before or after the annealing step.

In another aspect of the invention, instead of annealing, the chemically crosslinked implant is remelted to stabilize it against long-term oxidation. This can be achieved, e.g., by remelting the partially formed crosslinked material after crosslinking but prior to final shaping into the implant. In this case, either the surface destined to be the bearing surface of the implant is remelted, or the whole partially formed crosslinked material is remelted. If remelting is employed, the implant need not be annealed after crosslinking to stabilize its size and shape, since the remelting would also stabilize the size and shape of the implant. The implant or the partially formed crosslinked material may additionally be soaked in suitable solvent(s), as described above, to extract from the crosslinked surface layer any residual chemicals, either before or after remelting and/or reshaping of the implant.

Another aspect of the invention presents a method of treating a patient in need of an implant. An implant, or an implant with a bearing surface, composed of the surface-crosslinked PE is applied to the body of the patient, e.g., surgically implanted into the patient. The surface-crosslinked PE of the present invention has reduced wear rate. In the preferred embodiment, the bearing surface of the implant is composed of the surface-crosslinked PE. Known surgical methods for introducing an implant into a patient may be used.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 schematically shows an UHMWPE acetabular cup being exposed to e-beam radiation. A thin shield of steel or

other suitable material may be placed over those regions where crosslinking is not desired (e.g., the non-bearing surfaces).

FIG. 2 schematically shows an UHMWPE acetabular cup in a cup mold, with a thin layer of UHMWPE powder that has been mixed with peroxide to form a thin crosslinked layer at the bearing surface, with uncrosslinked UHMWPE below this layer to preserve the original physical properties of the UHMWPE.

FIG. 3 graphically presents the peak melting temperature vs distance from the e-beam crosslinked surface of UHMWPE specimens.

FIG. 4 graphically presents the gel content vs distance from the e-beam crosslinked surface of UHMWPE specimens.

FIG. 5 graphically presents the peak melting temperature vs distance from the peroxide crosslinked surface of UHMWPE specimens.

FIG. 6 graphically presents the gel content vs distance from the peroxide crosslinked surface of UHMWPE specimens.

FIG. 7 graphically presents the melting temperature and gel content profiles of the peroxide crosslinked surface of UHMWPE specimens.

FIG. 8 graphically presents the extraction of tertiary alcohol from 1 wt% peroxide crosslinked UHMWPE specimens.

FIG. 9 graphically presents the oxidation depth profiles of aged e-beam (at 5 Mrad) crosslinked UHMWPE specimens with or without hydrogen and/or ethylene oxide treatments.

FIG. 10 graphically presents the oxidation depth profiles of aged e-beam (at 10 Mrad) crosslinked UHMWPE specimens with or without hydrogen and/or ethylene oxide treatments.

FIG. 11 graphically presents the oxidation depth profiles of aged e-beam (at 15 Mrad) crosslinked UHMWPE specimens with or without hydrogen and/or ethylene oxide treatments.

FIG. 12 schematically presents a partially formed

acetabular cup.

FIG. 13 schematically presents the direction of electron beam radiation for: (A) a specimen placed flat on a table; and (B) a specimen mounted on a rotary motor tilted at an angle of 45 degree.

FIG. 14 graphically presents the profile of peak melting temperature versus distance from the surface of a surface-crosslinked partially formed cup irradiated to 10 MRad while the cup was placed on a stationary flat surface.

FIG. 15 graphically presents the profile of peak melting temperature versus distance from the surface of a surface-crosslinked partially formed cup irradiated with the e-beam at a 45 degrees to the central axis of the cup, to 10 Mrad on the cup surface and to 5 Mrad at 1 mm from the cup surface.

FIG. 16 graphically presents the profiles of oxidation versus distance from the surface of a surface-crosslinked partially formed cup after e-beam irradiation to 10 Mrad in the surface layer, and after annealing in vacuum at various temperatures for 3 days.

FIG. 17 graphically presents the profiles of peak melting temperature versus depth from the surface of a non-crosslinked cup (control) and for cups with surface layers crosslinked using 1% peroxide, comparing the profiles for cores taken from the bottom center of the cup and at 45 degrees from the bottom.

FIG. 18 graphically presents the profiles of oxidation ratio versus distance from the surface of surface-crosslinked partially formed acetabular cups after e-beam irradiation at the noted radiation doses. Some of the partially formed acetabular cups were not annealed. Others were then annealed in vacuum at 100°C for 3 days. All of the partially formed acetabular cups were then artificially aged for 20 days.

FIG. 19 graphically presents the profiles of oxidation ratio versus distance from the surface of surface-crosslinked partially formed acetabular cups after e-beam irradiation at the noted radiation doses. Some of the

partially formed acetabular cups were not annealed. Others were then annealed in vacuum at 100°C for 3 days. All of the partially formed acetabular cups were then artificially aged for 30 days.

FIG. 20 graphically presents the profiles of oxidation ratio versus distance from the surface of surface-crosslinked partially formed acetabular cups after e-beam irradiation at the noted radiation doses and then annealing in vacuum at 100°C for 6 days, but without aging.

FIG. 21 graphically presents the profiles of oxidation ratio versus distance from the surface of surface-crosslinked partially formed acetabular cups after e-beam irradiation at the noted radiation doses, annealing in vacuum at 100°C for 6 days, and then artificially aging for 20 days.

FIG. 22 graphically presents the profiles of oxidation ratio versus distance from the surface of surface-crosslinked partially formed acetabular cups after e-beam irradiation at the noted radiation doses, annealing in vacuum at 100°C for 6 days, and then artificially aging for 30 days.

FIG. 23 graphically presents the wear profiles in milligrams ("mg") of acetabular cups surface-crosslinked at the noted doses of e-beam irradiation and then annealed in vaccum at 100°C for three days; and acetabular cups surface-crosslinked with peroxide and annealed in vaccum at 80°C for 16 hours.

FIG. 24 graphically presents the profiles of oxidation ratio versus distance from the surface of artificially aged peroxide-crosslinked UHMWPE blocks with or without subsequent remelting.

DETAILED DESCRIPTION OF THE INVENTION

(I) Implants of the Present Invention

Chemical crosslinking of UHMWPE has been proven to substantially reduce the wear of UHMWPE hip acetabular cups

when tested in a wear simulator. EP 0722973 A1, "Chemically Crosslinked Ultrahigh Molecular Weight PE for Artificial Human Joints" of R. Salovey, et al., published July 24, 1996. In addition, appropriate amounts of crosslinking induced by gamma radiation or e-beam radiation, which crosslinked the entire bulk of an UHMWPE specimen, produced comparably low wear rates (WO 98/01085 of The Orthopaedic Hospital et al., published on January 15, 1998, entitled "Crosslinking of Polyethylene for Low Wear Using Radiation and Thermal Treatments"; Jasty, M., et al., "Marked Improvement in the Wear Resistance of a New Form of UHMWPE in Physiologic Hip Simulator", Transactions of the 43rd Ann. Mtg, Orthopaedic Research Society, p. 785, Feb. 9-13, 1997, San Francisco, California; and WO 97/29793 of Massachusetts Institute of Technology et al., published on August 21, 1997, entitled "Radiation and Melt Treated Ultra High Molecular Weight Polyethylene Prosthetic Devices").

However, crosslinking a PE may adversely affect its other physical properties, resulting in reductions in one or more of the following: Young's modulus, impact strength, fatigue strength, yield stress, tensile strength at break, and elongation at break. These reductions may, in turn, negatively affect the overall performance *in vivo* of an implant made from the crosslinked PE. Thus, a method which improves the wear resistance of the bearing surface of a PE implant, while minimizing the reduction in these mechanical properties in the bulk of the implant, would be advantageous.

Since the average clinical wear rate of conventional UHMWPE used in making acetabular cups for hip replacement, as reported in various studies in the literature, is typically about 100 to 200 microns per year, and since appropriately crosslinked UHMWPE (e.g., chemically or radiation crosslinked UHMWPE of EP 0722973 A1, and WO 98/01085, above) exhibits a twenty-fold or lower wear rate, then an appropriately crosslinked UHMWPE can be expected to wear only about 5 to 10 microns/year in typical clinical use. Applicants realized that, at this lower wear rate,

about 100 to 200 years would be required to wear through a one-millimeter (i.e., 1000 micron) thick surface layer of crosslinked UHMWPE, i.e. far longer than the life expectancy of the patient.

Thus, one aspect of the invention presents a new surface-crosslinked PE, or an implant made with surface-crosslinked PE. These PE and implants are more wear resistant in the crosslinked surface layer than their uncrosslinked counterparts, while maintaining the good physical properties in the bulk of the implant. The PE is preferably HMWPE and/or UHMWPE. The surface of the implant, preferably the bearing surface which may include any surface which is susceptible to wear, is appropriately crosslinked, with the crosslinking preferably gradually diminishing, preferably to zero crosslinking, below this layer to provide a gradual transition of physical properties to those of the conventional HMWPE or UHMWPE. The gradual transition is preferred so that there is not a weak interface that could delaminate, i.e., due to a sudden change from crosslinked to non-crosslinked material.

While it is most preferable to crosslink the intended bearing surface, e.g., the inner concave surface of an acetabular cup which articulates against the opposing femoral ball, it may be desirable also to crosslink any surface which is susceptible to wear due to moving contact with another surface (e.g., in a sliding, pivoting, or rotating relationship to one another), whether or not such motion is intended, such as the backside of a UHMWPE liner of a hip acetabular cup where it presses against the inside of the metal shell. Thus, the term "bearing surface" may also include any surface which is susceptible to wear or for which a user desires to improve its wear resistance.

Thus, for a particular implant made of PE, the depth of crosslinking in the bearing surface is preferably at least the thickness of the PE which would be worn away in a patient's lifetime. For example, the implant may have a maximum gel content of from about 80 to about 100% (more preferably from about 90 to about 100%, and most preferably

about 95%) within the bearing surface, which gradually decreases to about 50% of the maximum value at about 0.5 mm to about 2 mm from the surface of the implant, and tapering to nearly zero by about 2 mm to about 2.5 mm from the surface of the implant. These ranges are particularly suitable for an acetabular cup, where the bearing surface is its inner bearing surface and/or the backside of the acetabular cup where it presses against the inside of the metal shell; these ranges will leave the core of the acetabular cup nearly uncrosslinked.

Thus, instead of using the preferred range of radiation dose, discussed below, as a criterion, the appropriate amount of crosslinking may be determined based on the degree of swelling, gel content, or molecular weight between crosslinks after thermal treatment. This altenative is based on the applicant's findings that acetabular cups made from UHMWPE falling within a preferred range of these physical parameters have reduced wear. The ranges of these physical parameters in the surface region of the surface-crosslinked PE or product include one or more of the following: a degree of swelling of between about 1.7 to about 5.3; molecular weight between crosslinks of between about 400 to about 8400 g/mol; and a gel content of between about 90% to about 99%.

A preferred surface-crosslinked PE or final product has one or more, and preferably all, of the above characteristics. These parameters can also be used as starting points for determining the desired radiation dose to balance the improvement in wear resistance with other desired physical or chemical properties, such as PE strength or stiffness. Such balancing method is further described in WO 98/01085, hereby incorporated by reference in its entirety. Based on the teaching of the present application, one skilled in the art may, without undue experimentation, modify the above balancing method to achieve the present invention by using the e-beam irradiation and surface-crosslinking method of the present invention.

Examples of the methods for achieving such surface-crosslinked PE and implants are set forth below. Clearly,

one skilled in the art will realize that such implants and PE can also be made by other crosslinking methods known in the art and modified, according to the teaching presented herein, to produce such materials.

The preferred PE for use in the present invention generally possesses molecular weight of about 10^5 grams per mole or greater. The PE are generally between about 4×10^5 to about 10^7 grams per mole. HMWPE and UHMWPE are preferred. HMWPE have molecular weights ranging from about 10^5 grams per mole to just below 10^6. UHMWPE have molecular weights equal to or higher than 10^6 grams per mole, preferably from 10^6 to about 10^7.

For implants, the preferred PE are those that are wear resistant and have exceptional chemical resistance. UHMWPE is the most preferred PE, as it is known for these properties and is currently widely used to make acetabular cups for total hip prostheses and components of other joint replacements. Examples of UHMWPE are those having a molecular weight ranging from about 1 to 8×10^6 grams per mole, examples of which are: GUR 4150 or 4050 (Hoechst-Celanese Corporation, League City, Texas) with a weight average molecular weight of 5 to 6×10^6 grams per mole; GUR 4130 with a weight average molecular weight of 3 to 4×10^6; GUR 4120 or 4020 with a weight average molecular weight of 3 to 4×10^6; RCH 1000 (Hoechst-Celanese Corp.) with a weight average of molecular weight of 4×10^6 and HiFax 1900 of 2 to 4×10^6 (HiMont, Elkton, Maryland). Historically, companies which make implants have used PE such as HIFAX 1900, GUR 4020, GUR 4120 and GUR 4150 for making acetabular cups.

The surface-crosslinked PE and implants are useful as prostheses for various parts of the body, such as components of a joint in the body. For example, in the hip joints, they can be a prosthetic acetabular cup (as exemplified above), or the insert or liner of the cup, or a component of a trunnion bearing (e.g. between the modular head and the stem). In the knee joint, they can be a prosthetic tibial plateau (femoro-tibial articulation), patellar button

(patello-femoral articulation), and trunnion or other bearing components, depending on the design of the artificial knee joint. For example, in knees of the meniscal bearing type, both the upper and lower surfaces of the UHMWPE component may be surface-crosslinked, i.e., those surfaces that articulate against metallic or ceramic surfaces. In the ankle joint, they can be the prosthetic talar surface (tibio-talar articulation) and other bearing components. In the elbow joint, they can be the prosthetic radio-humeral joint, ulno-humeral joint, and other bearing components. In the shoulder joint, they can be used in the glenoro-humeral articulation, and other bearing components. In the spine, they can be used in intervertebral disk replacement and facet joint replacement. They can also be made into temporo-mandibular joint (jaw) and finger joints. The above are by way of example, and are not meant to be limiting.

For ease of discussion, this patent application often uses UHMWPE and acetabular cup implants as examples of PE and implants, respectively. However, it is to be understood that the present invention is applicable to PE in general; to implants in general; and in general to any desired products that may be made of PE.

(II) E-beam Crosslinking

In one aspect of the invention, the bearing surface of the UHMWPE cup is crosslinked using e-beam irradiation. The higher the energy of the e-beam, the deeper the penetration into the PE and, thus, the deeper the resultant crosslinking. A 10 MeV e-beam, such as used by Streicher and by Jasty, M., et al., above, and commercially used, would penetrate about 40 to 50 millimeters of an UHMWPE specimen.

In contrast, the present invention uses an e-beam with an energy of much less than 10 MeV, and preferably less than about 1 MeV. For example, in EXAMPLE 1, below, 0.875 MeV and 0.650 MeV were used. With MeV in this lower range, the bearing surface of an acetabular cup can be rendered more

wear resistant to a sufficient depth that it will not be worn through in the patient's lifetime, while keeping the rest of the acetabular cup non-crosslinked to retain the excellent mechanical properties of the conventional UHMWPE.

The e-beam dose in the surface layer to be crosslinked is preferably from about 1 to about 25 Mrad, more preferably from about 5 to about 20 Mrad, and most preferably from about 10 to about 20 Mrad. The dose preferably gradually tapers off to about 50% of the maximum value at about 0.5 mm to 2 mm into the cup. For example, a 10 Mrad dose may be applied in the bearing surface layer of the cup, the radiation dose gradually tapering off to 50% of the maximum value, i.e., 5 Mrad, at a depth of about 1 mm, and finally tapering to zero at a depth of 2 mm into the cup.

During crosslinking with an e-beam, the UHMWPE cups or partially formed cups (e.g., of Methods 1 to 3, below) may be enclosed in a low-oxygen atmosphere, e.g., of inert gas, such as nitrogen, or in vacuum, to minimize oxidation of the surface layer during irradiation.

In addition, particularly for cups irradiated in air, the implant can initially be fabricated slightly undersize and then, after irradiation and treatment to reduce the residual free radicals, the outermost surface layer (e.g., a few hundred microns, such as 100 to 300 microns) in the bearing region can be machined away to remove the most oxidized material, which typically has a reduced wear resistance compared to the less oxidized material immediately beneath this layer. In this case, the depth of the initial crosslinking could be increased (e.g., by using a higher energy beam), such that, after the oxidized surface is machined away, the remaining crosslinked layer would be of the desired thickness. The thickness of the most oxidized surface layer to be removed can be determined for a given process, for example by determining its gel content profiles using the method as shown in EXAMPLE 1, and producing a graph similar to that of FIG. 4, which shows the depth of the lower gel content (least crosslinked) region near the irradiated surface.

Ethylene oxide treatment, e.g., using methods known in the art for ethylene oxide sterilization of implants, has the additional benefit of decreasing the susceptibility to oxidation of e-beam irradiated PE (and, thus, increasing its long term wear resistance, see e.g., EXAMPLE 4, below) by reducing any residual free radicals resulting from e-beam radiation. The duration of ethylene oxide treatment may be shortened or extended according to the desired amount of reduction of free radicals.

The following provides three non-limiting examples for carrying out the crosslinking process:

Method 1: E-beam Irradiation of an Acetabular Cup

In this method, an acetabular cup is irradiated with e-beam at a temperature below its melt temperature, such as at room temperature, to produce surface-crosslinking of its bearing surface. With curved bearing surfaces, such as the inner concave surface of the acetabular cup, several methods may be used to distribute the dose of crosslinking over the entire bearing surface more uniformly. For example, the implant may be exposed to the e-beam in several passes, with the implant re-positioned between each partial irradiation in order to produce a more uniform distribution over the entire bearing surface. Alternatively, the implant may be rolled through the beam, such that the dose is spread more uniformly around the exposed surface. EXAMPLE 5, below, shows other methods of irradiating the cups, such as placing a cup on a stationary flat surface at a 90 degree angle incident to the e-beam [FIG. 13(A)] or having the e-beam scan the cup at an angle and crosslinking the cup throughout its surface, such as can be achieved by rotating the cup and keeping it at an angle of 45 degrees incident to the e-beam as shown in FIG. 13 (B). It should be noted that it is not essential that the profile of crosslinking be precisely uniform throughout the bearing surface of the cup. It is only necessary that the points on the cup surface which are susceptible to wear, have an adequate amount of crosslinking

and depth. Whichever technique is used, the appropriate combination of beam oscillation angle and exposure time to produce the desired dose in the surface layer of the implant can be calculated by one skilled in the art.

Since it may be desirable to crosslink only the bearing surfaces, a shield (e.g., a metal such as steel) may be placed over those areas of the cup that are not intended to be crosslinked, to shield them from the e-beam.

Although FIG. 1 schematically shows an abrupt boundary between the crosslinked surface layer and the non-crosslinked material, in practice this is preferably a gradual transition to uncrosslinked material beneath the surface layer.

In order to minimize long-term oxidation caused by residual free radicals generated by the crosslinking irradiation (and thus improve the long-term wear resistance), the irradiated acetabular cups can be treated with one or more of the following: pressurization in hydrogen, annealing, and treatment with ethylene oxide to reduce or eliminate the residual fee radicals.

The irradiated cup can be annealed by heating it below the melting temperature of the non-crosslinked PE. The annealing temperature is preferably selected to avoid excessive distortion of the crosslinked surface and/or the crosslinked implant. It should be noted that it is not essential that the profile of crosslinking be precisely uniform throughout the bearing surface of the cup. It is only necessary that the points on the cup surface which are susceptible to wear, have an adequate amount of crosslinking and depth.

As used in this patent application, the melting temperature is identified from the peak of the melting endotherm as measured by differential scanning calorimetry (DSC). The annealing temperature is preferably from about room temperature to below the melting temperature of the non-crosslinked region in the cup; more preferably from about 90°C to about 10°C below the melting temperature; and most preferably from about 80°C to about 50°C below the

melting temperature. UHMWPE may be annealed at a temperature from about 25°C to about 132°C, preferably from about 40°C to about 120°C, and more preferably from about 50°C to about 80°C.

Generally, in practice, the higher the annealing temperature the shorter the annealing time needed. The annealing period is preferably from about 2 hours to about 10 days, and more preferably from about 7 hours to about 8 days, and most preferably from about 10 hours to about 6 days.

Alternatively, the irradiated implant may be treated with hydrogen to further reduce or eliminate free radicals. A hydrogen treatment method is illustrated in EXAMPLE 4, below. One skilled in the art, based on EXAMPLE 4, would be able by simple trial and error without undue experimentation to arrive at the appropriate parameters for eliminating or reducing the desired amount of free radicals. Examples of minimum and maximum starting points for such trial and error would be pressurizing the cup in hydrogen to about 30 psi for about 18 hours, or to about 90 psi for about 72 hours, respectively.

<u>Method 2: E-beam Irradiation Followed by Remelting or Annealing</u>

In this method, instead of starting with an acetabular cup, a partially formed cup is used. This partially formed cup consists of the original bulk material (e.g., extruded PE bar, billet, or molded block) from which is shaped, e.g., by machining, the intended bearing surface of the cup. This bearing surface is then e-beam irradiated as in Method 1, above. The irradiated partially formed cup is then remelted or annealed, either in air or in a low oxygen atmosphere, to reduce free radicals and increase long term wear resistance. Remelting is a very effective and efficient method to reduce free radicals.

The remelting temperature is at or above the melting temperature of the maximum crosslinked region in the cup.

Preferably, the remelting temperature is from about such melting temperature to about 100°C to about 160°C above the melting temperature; more preferably from about 40°C to about 80°C above the melting temperature; and most preferably from about 1°C to about 60°C above the melting temperature. For example, in the case of UHMWPE, the remelting temperature is preferably from about 134°C to about 300°C, more preferably from about 134°C to about 250°C, and most preferably from about 134°C to about 200°C.

Generally, in practice, the higher the melting temperature, the shorter the melting time needed to achieve a particular amount of reduction of the free radicals. The PE is preferably remelted over a period from about 1 hour to about 2 days, more preferably from about 1 hour to about 1 day, and most preferably from about 2 hours to about 20 hours.

Since, depending on the time and temperature applied, annealing can produce less of an effect than remelting on physical properties such as crystallinity, yield strength and ultimate strength, annealing may be used in place of remelting as a means for reducing the free radicals remaining in the PE after irradiation crosslinking, in order to maintain these physical properties within limits required by the user. If the resultant PE must have specific minimum physical properties, whether remelting is appropriate in view of its effect on these properties may be determined by methods known in the art, such as described in WO 98/01085. The appropriate combination of annealing or remelting temperature and time may be determined according to the methods described in WO 98/01085.

Annealing is slower and takes longer than remelting, and is most preferably conducted in a low oxygen environment, e.g., in a vacuum oven or in inert atmosphere. If annealing instead of remelting is employed, the annealing temperature is below the melting temperature of the non-crosslinked region in the cup, preferably from about room temperature to below the melting temperature; more preferably from about 90°C to about 1°C below the melting

temperature; and most preferably from about 60°C to about 1°C below the melting temperature. For example, UHMWPE may be annealed at a temperature from about 25°C to about 132°C, preferably from about 50°C to about 132°C, and more preferably from about 80°C to about 130°C. The annealing period is preferably from about 2 hours to about 10 days, and more preferably from about 7 hours to about 8 days, and most preferably from about 10 hours to about 6 days. The annealing temperature is preferably selected to avoid excessive distortion of the crosslinked surface and/or the crosslinked implant. Generally, for most UHMWPE, heating at or above 120°C may cause distortion in the PE, the preferable annealing temperature is about 100°C and the preferable annealing time is between about 3 to about 6 days. It should be noted that it is not essential that the profile of crosslinking be precisely uniform throughout the bearing surface of the cup. It is only necessary that the points on the cup surface which are susceptible to wear, have an adequate amount of crosslinking and depth.

The thermal treatment methods described in WO 98/01085 are also applicable to improve the resistance to oxidation and, thereby, the resistance to wear of the surface-crosslinked PE of the present invention. WO 98/01085 is hereby incorporated by reference in its entirety.

After the remelting or annealing, the final shape of the cup is fashioned, e.g., by machining out of the partially formed cup. Any distortion and/or oxidized layer of the PE caused by the remelting or annealing is thereby corrected or removed, respectively, in the process of the final shaping. In this case, the depth of the initial crosslinking would be increased,e.g., by increasing the energy of the e-beam, such that, after the final shaping, the remaining crosslinked layer would be of the desired thickness and degree of crosslinking.

Method 3: E-beam Irradiation in the Melt

Method 3 is the same as Method 2, except that the

partially formed cup is irradiated in the melt (at or above melting temperature of UHMWPE).

Given the teaching in this patent application, one skilled in the art can arrive at his desired surface-crosslinked PE and implant. For example, for PE of a given density, one skilled in the art can easily calculate the necessary dosage to achieve the desired penetration or crosslinking profile. As shown in EXAMPLE 1, one skilled in the art can, through preliminary calculations and/or straightforward trial-and-error, appropriately adjust the combination of the e-beam energy and the exposure time to obtain a desired maximum crosslinking in the surface layer and a rate of decrease below this layer, in order to get the required improvement in wear resistance in a surface layer of desired thickness.

(III) Chemical Crosslinking

In another aspect of the invention, the bearing surface layer of the acetabular cup is chemically crosslinked, while leaving non-crosslinked UHMWPE below the chemically crosslinked surface layer. FIG. 2 schematically shows the structure of this acetabular cup. Although the drawing shows an abrupt boundary between the crosslinked surface layer and the non-crosslinked material, in practice this is preferably a gradual transition, which leaves the interior of the PE uncrosslinked (see e.g., FIG. 7). The following provides two non-limiting methods for achieving such surface-crosslinked material.

Method A

PE powder is placed in an implant mold and then cold-pressed for a sufficient time to compact the powder, to a slight oversize of the interior diameter (I.D.) to allow for the addition of a crosslinked layer. Next, additional PE powder is mixed with a free radical generating chemical. The term "free radical generating chemical" is hereinafter referred to as "FRGC". If the FRGC is a peroxide, it can be

mixed with the PE powder while dry, or it can be dissolved in an inert solvent before being added to the PE powder. Examples of such inert solvents are alcohol and acetone. After the PE powder has been mixed with the inert solvent containing the peroxide, the inert solvent is then evaporated.

A thin layer of the PE powder with the FRGC is then placed on the area of the intended bearing surface on the previously compacted powder, and the combination is then further cold-pressed to compact both layers of powder. The compacted layers are then compression molded using standard methods known in the art for molding PE.

<u>Method B</u>

In this method, PE powder is placed in an implant mold and compression molded using methods known in the art to a slight oversize of the I.D. to allow for the addition of a crosslinked layer. A thin layer of PE powder mixed with FRGC is then placed over the intended bearing surface and cold-pressed to compact it, and then compression molded using methods known in the art, thereby simultaneously crosslinking the surface layer and fusing it to the bulk of the implant. Again, the FRGC can be a peroxide.

Alternatively, a PE implant can be partially formed by machining in the usual manner, but to a slight oversize of the I.D., and then placed in a mold with the bearing surface coated with a layer of PE powder mixed with a FRGC, and then heat and pressure applied to crosslink the mixture and simultaneously fuse it to the partially formed implant.

Thus, one skilled in the art can, by routine trial and error, modify the methods in EXAMPLE 2 to adjust the concentration of the FRGC used and/or the thickness of the layer of PE powder mixed with the FRGC applied and use the present invention in order to obtain a desired maximum level of crosslinking in the surface layer as well as a desired maximum depth of crosslinking.

i) Annealing of a Chemically Crosslinked Implant To Stabilize Its Size and Shape

A chemically crosslinked implant may be annealed to reduce residual stresses and shrink it to a stable size and shape before final shaping the cup into the final product. The annealed cup may be re-sized or shaped, such as by machining, into a product with the desired dimensions. The annealing temperature is preferably chosen to minimize distortion of the cup. Thus, the annealing temperature is preferably below the melting point of the molded PE. For example, the melting temperature of molded 1 weight percent (wt%) peroxide surface crosslinked UHMWPE is about 126°C. The preferable annealing temperature for this molded UHMWPE is between 60°C to 125°C, and more preferably about 100°C. The annealing time is generally between 1 to 6 hours, and more preferably between 2 to 4 hours. In the case of UHMWPE, the annealing time is preferably between 2 to 4 hours, and more preferably about 2 hours. To further avoid thermal oxidation of the crosslinked PE, the annealing is most preferably conducted in a low oxygen environment, e.g., in a vacuum oven or in inert atmosphere. The annealing temperature is preferably selected to avoid excessive distortion of the crosslinked material PE. It should be noted that it is not essential that the profile of crosslinking be precisely uniform throughout the bearing surface of the cup. It is only necessary that the points on the cup surface which are susceptible to wear have an adequate amount of crosslinking and depth.

ii) Chemical Crosslinking Followed by Remelting

Instead of annealing, the chemically crosslinked implant may be remelted to improve its oxidation resistance and, thus, improve its wear resistance. This can be done, e.g., by remelting the chemically crosslinked implant while it is still in its mold (either as a fully formed implant or a partially formed implant). The partially formed implant

can be made slightly undersized (i.e., slightly smaller I.D. than needed for the final product) prior to remelting, and the remelted partially formed implant is then shaped (e.g., by machining) into the final implant.

The remelting temperature is at or above the melting temperature of the maximum crosslinked region in the cup. Preferably, the remelting temperature is from the melting temperature to about 60°C above the melting temperature. For example, UHMWPE crosslinked with about 2 wt% of peroxide concentration has a melting temperature of 115°C, thus the remelting temperature is preferably from about 115°C to about 300°C, more preferably from about 115°C to about 200°C, and most preferably from about 115°C to about 155°C. In another example, the melting temperatures of molded 1 wt% peroxide surface crosslinked UHMWPE is about 126°C. Thus, the remelting temperature of molded 1 wt% peroxide crosslinked UHMWPE is preferably from about 126°C to about 300°C, more preferably from about 126°C to about 200°C, and most preferably from about 126°C to about 155°C.

Generally, in practice, the higher the melting temperature, the shorter the melting time needed to achieve a particular amount of reduction of the free radicals. The PE is preferably remelted over a period from about 1 hour to about 2 days, more preferably from about 1 hour to about 1 day, and most preferably from about 2 hours to about 20 hours.

<u>iii) Soaking of a Peroxide Crosslinked Implant</u>

For implants which are crosslinked by peroxide, after the crosslinking, residual chemicals may be removed from the crosslinked layer by soaking the implant, e.g., from 1 to 10 days, in suitable solvents, such as acetone or 95% alcohol. This soaking step may be conducted in addition to the annealing and/or remelting steps described above. This soaking step may be used before or after the annealing and/or remelting; and may be applied either to the implant or the partially formed implant. One skilled in the art may

use the method described in EXAMPLE 3 to determine the length of time for soaking his particular PE or implant to achieve his desired decrease or elimination of the peroxide.

iv) Examples of FRGC

Conventional methods for chemical crosslinking of UHMWPE which can be modified to produce the present surface-crosslinked UHMWPE and implants are described in e.g., de Boer, J. & Pennings, A.J., *Makromol. Chem. Rapid Commun.*, **2**:749 (1981); de Boer, J. & Pennings, A.J., *Polymer*, **23**:1944 (1982); de Boer, J., et al., *Polymer*, **25**:513 (1984) and Narkis, M., et al., *J. Macromol. Sci. Phys.*, **B 26**:37, 58 (1987). The method described in EP 0722973 A1, above may also be modified to produce the present novel UHMWPE and implants. For example, the crosslinking chemical, FRGC, may be any chemical that decomposes at the molding temperature to form highly reactive intermediates, free radicals, which would react with the PE to form the crosslinked network. Examples of FRGC are peroxides, peresters, azo compounds, disulfides, dimethacrylates, tetrazenes, and divinyl benzene. Examples of azo compounds are: azobis-isobutyronitride, azobis-isobutyronitrile, and dimethylazodi isobutyrate. Examples of peresters are t-butyl peracetate and t-butyl perbenzoate.

Preferably, the PE is crosslinked by treating it with an organic peroxide. The preferable peroxides are 2,5-dimethyl-2,5-bis(tert-butylperoxy)-3-hexyne (Lupersol 130, Atochem Inc., Philadelphia, Pennsylvania); 2,5-dimethyl-2,5-di-(t-butylperoxy)-hexane; t-butyl alpha-cumyl peroxide; di-butyl peroxide; t-butyl hydroperoxide; benzoyl peroxide; dichlorobenzoyl peroxide; dicumyl peroxide; di-tertiary butyl peroxide; 2,5 dimethyl-2,5 di(peroxy benzoate) hexyne-3; 1,3-bis(t-butyl peroxy isopropyl) benzene; lauroyl peroxide; di-t-amyl peroxide; 1,1-di-(t-butylperoxy) cyclohexane; 2,2-di-(t-butylperoxy)butane; and 2,2-di-(t-amylperoxy) propane. The more preferred peroxide is 2,5-dimethyl-2,5-bis(tert-butylperoxy)-3-hexyne. The preferred

peroxides have a half-life of between 2 minutes to 1 hour; and more preferably, the half-life is between 5 minutes to 50 minutes at the molding temperature. The preferred peroxide concentration is from 0.2 to 2 wt%; preferably from 0.2 wt% to 1 wt%; and more preferably from 0.4 wt% to 1.0 wt%. The most preferred peroxide is 2,5-dimethyl-2,5-bis(tert-butylperoxy)-3-hexyne which is preferably used at about 1 to 2 wt%, and most preferably at 1 wt%. The peroxide can be dissolved in an inert solvent before being added to the PE powder. The inert solvent preferably evaporates before the PE is molded. Examples of such inert solvents are alcohol and acetone.

(IV) Sterilization

The implants of the present invention may be sterilized using methods known in the art, such as by ethylene oxide, gas plasma or gamma irradiation sterilization. Ethylene oxide sterilization has the additional benefit of decreasing the oxidation susceptibility of electron irradiated PE (and, thus, increasing the long term wear resistance, see e.g., EXAMPLE 4, below) by reducing any residual free radicals resulting from e-beam radiation.

(V) Other Applications

i) Surface-Crosslinking Raw Materials

The present invention provides methods for producing surface-crosslinked PE. For convenience, the above discussion uses implant and partially formed implant to illustrate the present invention. One skilled in the art would realize that surface-crosslinked PE of the present invention can be used in any situation where a polymer is called for, but especially in situations where high wear resistance is desired. For example, the surface-crosslinked PE may be made into any products, e.g., products which are traditionally made of PE, or products which require a wear

resistant surface. Further, the surface-crosslinked PE of the present invention may be used as the surface, e.g., a bearing surface, alone or layered (e.g., mechanically applied, chemically grafted or bonded) over another material or product. Thus, the above methods are appropriate and may be modified by one skilled in the art to apply to other PE products and surfaces.

In yet another embodiment of the invention, instead of applying the above methods to a partially formed product (such as a partially formed implant) or fully formed product (such as an implant), the methods are applied to the raw materials of PE. Thus, the above methods may be modified by one skilled in the art to apply to the raw materials of PE.

For example, an extruded PE bar, PE billet, or PE molded block may be surface-crosslinked with e-beam irradiation, remelted or annealed, and then formed using methods known in the art (e.g. by machining) into a desired product. In yet another example, PE powder may be placed in a mold and then compacted (e.g., by applying pressure to the powder such as by cold-press, for example, as described in the section: "(III) Chemical Crosslinking", above, and in EXAMPLE 2, below). The compacted powder, still in the mold, may then be surface-crosslinked with e-beam irradiation, and then compression molded using methods known in the art. Traditional compression molded methods use high temperature and/or high pressure (such as described in the section: "(III) Chemical Crosslinking", above, and in EXAMPLE 2, below), these methods would thus serve to simultaneously remelt the surface-crosslinked PE to improve its wear resistance and stabilize its size and shape. The resulting molded item may then be formed using methods known in the art (e.g. by machining) into a desired product. The above surface-crosslinked bar, billet, block, PE powder compression molded product, or the desired product may further be treated by exposure to hydrogen, ethylene oxide or annealing to improve its oxidation resistance, and annealed to stabilize its size and shape, as discussed above.

As another example, an extruded PE bar, PE billet, PE molded block, or PE powder in a mold, may be surface-crosslinked by FRGC, as described above. The resulting surface-crosslinked PE is then formed (e.g. by machining) into a desired product.

The crosslinked bar, billet, block, molded powder, or the desired product may be further treated by annealing to stabilize its size and shape, and/or improve its oxidation resistance, or remelting to improve its oxidation resistance, or soaked in solvent(s) to remove the residual chemicals resulting from decomposition of the FRGC.

The invention may be better understood with reference to the accompanying examples, which are intended for purposes of illustration only and should not be construed as in any sense as limiting the scope of the invention as defined in the claims appended hereto.

EXAMPLES

EXAMPLE 1
SURFACE CROSSLINKING WITH LOW ENERGY E-BEAM IRRADIATION

Materials

Commercial-grade UHMWPE extruded bars (GUR 1050, 3" diameter, Poly Hi Solidur, Ft Wayne, IN), with a weight average molecular weight of from 5 x 10^6 to 6 x 10^6 gram per mole, were used as received. The 8 mm thick disk specimens were cut from the bars and irradiated with an e-beam at room temperature in nitrogen atmosphere at Radiation Dynamics, Inc. (New York, New York) to doses ranging from 5 to 15 Mrad. To produce materials with surface crosslinking but with the interior uncrosslinked, one set of specimens was irradiated at 0.875 MeV at a dose rate of 1.35 Mrad/sec, producing a surface dose of 5 Mrad that dropped to 2.5 Mrad at a depth of about 2 mm and to nearly zero at about 2.5 mm (FIG. 3), another set of specimens was irradiated at 0.650 MeV at a dose rate of 1.35 Mrad/sec to obtain a surface dose

of 10 Mrad, decreasing to about 5 Mrad at a depth of 1 mm and to nearly zero at about 1.5 mm, and the third set of specimens was irradiated at 650 kV at a dose rate of 1.35 Mrad/sec to obtain a surface dose of 15 Mrad, decreasing to about 7.5 Mrad at a depth of 1 mm and to nearly zero at about 1.5 mm deep. After irradiation, the specimens were stored in nitrogen atmosphere. The physical properties of the irradiated specimens were characterized by differential scanning calorimetry (DSC) and by gel content analysis (to indicate the extent of crosslinking).

DSC

For DSC measurements, a core about 5 mm dia. was cut from the sample and the core was microtomed into 200 μm thick sections across the depth. Specimens weighing about 4 mg were heated from 50°C at 10°C/min in a differential scanning calorimeter (Perkin-Elmer DSC-4) to 170°C. The melting temperature was identified from the peak of the melting endotherm. Indium was used for calibration of the temperature.

Gel Content Analysis

The gel content of each material was analyzed as a function of depth from the crosslinked surface. 100 μm thick sections (about 30 - 50 mg each) were microtomed across the specimen. Extraction of the sol-fraction was performed by boiling in p-xylene for 24 hours, with 0.5 wt% of antioxidant (2,6-di-t-butyl-4-methyl phenol) added to prevent oxidation. For lightly crosslinked sections below the highly crosslinked surface, the specimens were wrapped in PTFE (Teflon) membrane filter (0.5 μm pore size) to avoid loss of gel. After extraction, the specimens were de-swollen in acetone and dried at 60°C in a vacuum oven to constant weight. The gel fraction was determined from the ratio of the weight of the dried-extracted material to that of the dry non-extracted material.

Results and Discussion

As shown in FIG. 3, e-beam irradiation increased the melting temperature of the crosslinked surface layer of the 8 mm thick UHMWPE specimens. There was a strong gradient in melting temperature for all irradiated specimens. The melting temperature decreased gradually with depth and, eventually, there was no temperature increase in the interior, indicating that no crosslinking had occurred. The crosslinking depth depended on the energy of the e-beam. The dose at a given depth depended on the exposure time. For example, the crosslinking depth extended to about 3 mm deep with the 0.875 MeV beam (5 Mrad specimens) and about 1.8 mm deep with the 0.650 MeV beam (10 and 15 Mrad specimens). There was a greater increase in melting temperature with increasing radiation dosage (FIG. 3). The gel content (i.e., the extent of crosslinking, FIG. 4) also increased with increasing radiation dosage, with the maximal gel contents being about 93, 95 and 96 % for 5, 10 and 15 Mrad specimens, respectively.

EXAMPLE 2

SURFACE CHEMICALLY-CROSSLINKED UHMWPE MADE WITH PEROXIDE

Materials

Commercial-grade UHMWPE flake (GUR 1050, Poly Hi Solidur), with a weight average molecular weight of from 5 x 10^6 to 6 x 10^6 gram per mole, was used as received. The peroxide was 2,5-dimethyl-2,5-bis(tert-butylperoxy)-3-hexyne (Lupersol 130, Atochem Inc., Philadelphia). Mixing of the UHMWPE and the peroxide was accomplished by dispersing UHMWPE powder in an acetone solution of the peroxide and subsequently evaporating the acetone (using the method described in EP 0722973 A1, "Chemically Crosslinked Ultrahigh Molecular Weight Polyethylene for Artificial Human Joints" of R. Salovey, et al.). The surface-crosslinked UHMWPE specimens were synthesized according to the following procedures:

Method A

The original UHMWPE powder was placed in a rectangular mold (dimension 8.8 x 3.7 x 2.8 cm) and then cold-pressed at room temperature and 2000 psi pressure on the powder for 10 minutes. A layer of UHMWPE powder mixed with either 1 wt% or 0.2 wt% peroxide (the layer was about 0.5 mm for 1 wt% peroxide; and about 1.0 mm for 0.2 wt% peroxide) was then placed on the compacted powder and the combination was then further cold-pressed at room temperature and 2000 psi pressure for 10 minutes. The compacted mixture was then heated to 170°C under a 1000 psi pressure on the powder for 2 hours, and then slow-cooled to room temperature while held at 2000 psi pressure.

Method B:

The original UHMWPE powder was placed in the rectangular mold, heated to 170°C under 1000 psi pressure on the powder for 1 hour and subsequently slow-cooled at 2000 psi pressure to below 100°C. A layer about 0.5 mm thick of UHMWPE powder mixed with 1 wt% peroxide was then placed on the top of the molded block and the block was cold-pressed at 2000 psi pressure for 10 minutes, heated to 170°C for 2 hours at 1000 psi pressure, and then slow-cooled to room temperature while held at 2000 psi pressure. The physical properties of the specimens surface-crosslinked by Methods A or B were characterized by DSC and gel content analysis, as described in EXAMPLE 1.

Results and Discussion

The melting temperatures and gel content profiles of the surface-crosslinked UHMWPE produced with Method A are shown in FIGs. 5-6, respectively. Unlike radiation crosslinked specimens (FIG. 3), for which the melting temperature was increased by crosslinking, with peroxide crosslinking during molding, the melting temperature of the specimens decreased after crosslinking, due to the specimens recrystallizing in a crosslinked melt. The more the peroxide, the lower the melting temperature (FIG. 5). There

was a strong gradient in melting temperature for specimens crosslinked with both 0.2 and 1 wt% peroxide. The interpenetration of the peroxide-mixed and non-mixed UHMWPE and the diffusion of peroxide during molding resulted in the crosslinked layer penetrating about 4 mm into the PE. With 1 wt% peroxide crosslinking, the surface layer (about 1 mm thick) exhibited almost a 100% gel content (FIG. 6), gradually decreasing to about 60% at about 4 mm deep. In contrast, with 0.2 wt% peroxide crosslinking, the gel content was about 90% in the surface layer, decreasing more rapidly with depth and becoming effectively zero at a depth of about 3.3 mm.

The melting temperature and gel content profiles of the UHMWPE surface-crosslinked specimens using method B are shown in FIG. 7. Compared to the 1 wt% peroxide crosslinked specimen made with method A, the specimen made with method B exhibited steeper gradients in both the peak melting temperature and gel content (i.e., comparing FIG. 7 to FIGs. 5 and 6).

EXAMPLE 3

EXTRACTION OF RESIDUAL CHEMICALS RESULTING FROM PEROXIDE DECOMPOSITION

Materials

Commercial-grade GUR 4150 UHMWPE original flake (Hoechst, Texas), with a weight-average molecular weight of about from 5×10^6 to 6×10^6 gram per mole was used as received. Mixing of 1 wt% peroxide with the UHMWPE was as described in EXAMPLE 2, and crosslinked blocks, 8 mm thick, were prepared by heating the mixed powder at 170°C and 1000 psi pressure on the powder for 2 hours. After 2 hours, the pressure on the specimen was increased to 2000 psi and the specimen was slowly cooled in the press to room temperature. Rather than surface crosslinking, as in EXAMPLE 2, these specimens were crosslinked throughout the entire thickness in order to determine the depth of extraction of the solvents.

Specimens to be extracted were soaked in ethanol or acetone at room temperature for 7 days and then dried in a vacuum oven at 50°C overnight. The concentration of residual chemicals, as indicated by the tertiary alcohols, was examined using Fourier transform infrared spectroscopy (FTIR).

FTIR

FTIR measurements were performed on the extracted and non-extracted specimens. Segments about 5 mm wide were cut from each PE specimen and then microtomed into 200 μm thick slices. The tertiary alcohol profiles were measured using a Mattson Polaris spectrophotometer (Model IR 10410) with a Spectra-Tech IR plan microscope. Spectra were collected in 100 μm steps through the entire specimen, using 64 scans summation at a resolution 16 cm^{-1} with a MCT (Mercury Cadmium Telluride) detector. The tertiary alcohol concentration was indicated by the ratio of the peak height of the absorption band at 1173 cm^{-1} to the height of the reference band at 2022 cm^{-1} (i.e., representing the - CH_2 - vibration).

Results and Discussion

As shown in FIG. 8, extraction with ethanol or acetone reduced the tertiary alcohols to zero at the surface, with the concentration of tertiary alcohols increasing to about 40 to 50% of that of the non-extracted specimens at a depth of about 0.5 mm. Thus, one additional benefit of limiting the chemical crosslinking only to a surface layer is that the tertiary alcohols will primarily be present in the surface layer and, thus, more readily extracted with soaking in a solvent. Longer soak times would result in deeper extraction.

EXAMPLE 4

ARTIFICIAL AGING OF UHMWPE THAT HAS BEEN SURFACE-CROSSLINKED WITH E-BEAM IRRADIATION

Materials

The materials and irradiation methods were as described in EXAMPLE 1. The 8 mm thick UHMWPE specimens were surface-crosslinked with e-beam irradiation to 5, 10 or 15 Mrad while in a nitrogen atmosphere. After irradiation, specimens from each radiation dosage were subject to the following treatments: (1) stored in pressurized hydrogen atmosphere at 30 psi and room temperature for 18 hours; (2) sterilized with ethylene oxide after hydrogen treatment, using regular sterilization procedures; or (3) sterilized with ethylene oxide without hydrogen treatment. One set of specimens from each radiation dose was used as controls, i.e., without any post-irradiation treatments.

To examine the oxidation resistance of the irradiated specimens with or without post-irradiation treatments, the above specimens were heated in an oven slowly (at about 0.2 °C/min) to 80°C at ambient atmosphere and held at 80°C for 11 days. After this thermal aging, the extent of oxidation of the aged specimens was examined with FTIR as a function of depth.

FTIR

Segments about 5 mm wide were cut from each PE specimen and then microtomed into 200 μm thick slices. The oxidation profiles, as indicated by the carbonyl concentration, were measured using a Mattson Polaris FTIR spectrophotometer (Model IR 10410) with a Spectra-Tech IR plan microscope. Spectra were collected in 100 μm steps from the surface to the middle of the specimen, using 64 scans summation at a resolution 16 cm^{-1} with a MCT (Mercury Cadmium Telluride) detector. The carbonyl group concentration was indicated by the ratio of the peak height of the ketone absorption band at 1717 cm^{-1} to the height of the reference band at 2022 cm^{-1} ($-CH_2-$ vibration).

Results and Discussion

The oxidation profiles as a function of depth are shown in FIGs. 9 to 11. As shown in FIG. 9 for the 5 Mrad materials, hydrogen treatment or ethylene oxide sterilization apparently reduced the susceptibility of the material to oxidation, compared to the non-treated material, as indicated by the low oxidation ratio. The material treated with hydrogen and then sterilized with ethylene oxide exhibited the least oxidation, i.e., about 70% lower near the surface than in the non-treated material, indicating that both hydrogen treatment and/or ethylene oxide sterilization effectively reduce the residual free radicals resulting from e-beam irradiation.

After thermal aging, the oxidation was greater for higher radiation dosage (FIGs. 9 to 11). For the 10 Mrad materials (FIG. 10), ethylene oxide sterilization alone, or hydrogen treatment followed by ethylene oxide sterilization substantially reduced the residual free radicals, resulting in much lower oxidation, but there was little effect of hydrogen treatment alone, and there was little difference between the ethylene oxide specimens with or without hydrogen treatment. Similar results were obtained for the 15 Mrad materials (FIG. 11).

Although the hydrogen treatment of the time and pressures used in the present example had a marked effect only for the lower dose (5 Mrad) specimens, the effectiveness for the higher doses could be increased by increasing the time and/or pressure of exposure while at either room temperature or elevated temperature, thereby improving the resistance of the crosslinked surface layer to long-term oxidation. One skilled in the art can adjust these conditions, using routine trial and error, to decrease the long-term oxidation.

EXAMPLE 5

SURFACE-CROSSLINKED ACETABULAR CUP USING LOW-ENERGY E-BEAM IRRADIATION

Materials

Commercial-grade extruded bars of UHMWPE (GUR 1050, Poly Hi Solidur, Ft Wayne, IN), with a weight average molecular weight of 5 to 6 x 10^6, were used as received. A partially formed acetabular cup with 1.26" I.D. (FIG. 12) was machined from the bar and irradiated with an e-beam at room temperature in a nitrogen atmosphere at Radiation Dynamics, Inc. (New York), in order to produce acetabular cups with crosslinking of the bearing surface, but with the interior uncrosslinked. One set of three specimens was placed flat on a stationary table (FIG. 13A) and then irradiated at 650 keV at a dose rate of 1.35 Mrad/sec, to produce a surface dose of approximately 10 Mrad but dropping to 5 Mrad at a depth of about 1 mm, and to nearly zero at about 2 mm. To provide more uniform crosslinking around the interior of the cup, a second set of three specimens was mounted on a rotary motor tilted at an angle of 45 degrees to the incident e-beam (FIG. 13B), such that the cups rotated during exposure and were irradiated to a surface dose of approximately 10 Mrad, as described above. After irradiation, the specimens were stored in a nitrogen atmosphere. In order to reduce the residual radicals produced by the irradiation, thereby improving the long-term resistance to oxidation, some of the specimens (taken from the set irradiated at 45 degrees) were then annealed in a vacuum oven at either 80°C or 100°C for 3 days, which applicants have found to improve the resistance to oxidative degradation (data not shown).

In order to assess the amount of crosslinking as a function of depth, as well as the distribution of the crosslinking around the interior of the cups, core samples were cut from: (a) the bottom center of the cups, (b) at 45 degrees from the bottom center, and (c) near the rim of the cup, and were microtomed to 200 micron thick sections. The

thermal properties of the sections were characterized by DSC, as described in EXAMPLE 1. The degree of oxidation as a function of depth was assessed using FTIR on microtomed cross-sections of the cups, as described in EXAMPLE 4.

Results and Discussion

As shown in FIG. 14 for a cup that was irradiated while placed flat, the low-energy e-beam irradiation induced maximum crosslinking in the surface layer, as indicated by the increased melting temperature, that dropped to nearly zero crosslinking by about 2 mm deep, and the amount and depth of crosslinking was only slightly lower near the rim of the cup than at 45 degrees and near the bottom center.

As shown in FIG. 15, irradiating the cup with the e-beam at 45 degrees (FIG. 13) and rotating the cup during exposure produced a slightly more uniform distribution of the amount and depth of crosslinking than was obtained when the cup was irradiated while simply placed flat on a stationary table (FIG. 14).

Even after annealing, there was only minor oxidation at the surface (FIG. 16). Thus, the final shape of acetabular cup can be machined out of the irradiated-annealed partially formed cup simply by shaping the outer surface. Nevertheless, if the minor oxidation at the surface is a concern, the partially formed cups can be made slightly undersized (i.e., slightly smaller I.D. than needed for the final product) prior to irradiation, and the lightly oxidized layer can be removed during the final machining, thereby producing maximal crosslinking at the initial bearing surface.

EXAMPLE 6

SURFACE CHEMICALLY-CROSSLINKED UHMWPE ACETABULAR CUPS MADE WITH PEROXIDE CROSSLINKING

Materials

Commercial-grade UHMWPE flake (GUR 1050, Poly Hi Solidur), with a weight average molecular weight of 5 to 6 x

10^6, was used as received. The peroxide was 2,5-dimethyl-2,5-bis(tert-butylperoxy)-3-hexyne (Lupersol 130, Atochem Inc.). Mixing of the UHMWPE and the peroxide was as described in EXAMPLE 2. Surface-crosslinked UHMWPE acetabular cups (32 mm I.D.) were fabricated according to the following procedure: the original UHMWPE powder was placed in the mold in the shape of an acetabular cup, heated to 170°C under 1000 psi pressure on the powder for 1 hour, and subsequently slow-cooled at 2000 psi pressure to below 100°C. A layer of UHMWPE powder mixed with peroxide was then placed over the concave surface of the molded cup, the cup was cold-pressed at 2000 psi pressure for 10 minutes, heated to 170°C for 2 hours at 1000 psi pressure, and then slow-cooled to room temperature while held at 2000 psi pressure.

To assess the depth of crosslinking into the bearing surface, cylindrical cores 5 mm in diameter were machined out of the bottom center of the cup and at 45% from the bottom center, and the cores were microtomed into sections each 200 micron thick. The melting temperature as a function of depth was then characterized by DSC, as described in EXAMPLE 1.

Results and Discussion

The melting temperatures as a function of depth are shown in FIG. 17. With peroxide crosslinking, in contrast to irradiated cups (EXAMPLE 5), where the melting temperature increases after crosslinking, the melting temperatures of the cups that were crosslinked with peroxide decreased after crosslinking, due to the specimens having recrystallized in a crosslinked melt. Thus, the higher the concentration of peroxide that is mixed with the PE powder, the greater the resultant crosslinking, and the lower the melting temperature (FIG. 5). There was a strong gradient in melting temperature (i.e., a gradient in crosslink density) near the surface, reaching a plateau about 3 mm deep, indicating that the UHMWPE had little or no crosslinking deeper than about 3 mm (FIG. 17), as intended. Although the melting temperature profile was slightly lower for the core taken from the

bottom center of the cup, the overall similarity of the profiles of the melting temperature indicated that the crosslinking was nearly uniform at different locations in the cup.

These results demonstrated that, simply by adjusting the concentration of peroxide that is mixed with the original UHMWPE powder and/or adjusting the thickness of the layer of peroxide-mixed UHMWPE applied to the concave surface, the degree of crosslinking and/or the depth of penetration of the crosslinking into the bearing surface can be systematically modified by one skilled in the art.

EXAMPLE 7

ARTIFICIAL AGING OF ACETABULAR CUPS THAT HAVE BEEN SURFACE-CROSSLINKED USING LOW-ENERGY E-BEAM IRRADIATION

Materials and Methods

The grade of UHMWPE and details of producing surface-crosslinked acetabular cups using low-energy e-beam irradiation used in this example were described in EXAMPLE 5. A partially formed acetabular cup with 1.26" I.D. (FIG. 12) was machined from an extruded bar of UHMWPE and then irradiated with an e-beam at room temperature in a nitrogen atmosphere at Radiation Dynamics, Inc. (New York), in order to produce acetabular cups with crosslinking of the bearing surface, but with the interior not crosslinked. Partially formed acetabular cups were placed flat on a stationary table (FIG. 13A) and then irradiated at 650 keV at a dose rate of 1.5 Mrad/sec, to produce a radiation dose of 5, 10 and 15 Mrad in the surface layer, but dropping to about 50% of the surface dose at a depth of about 1 mm, and to nearly zero at about 2 mm (FIG. 14). A subset of partially formed acetabular cups for each dose were annealed in a vacuum oven at 100°C for either 3 or 6 days to remove residual free radicals and, thereby, improve the oxidation resistance.

To examine the oxidation resistance of the surface-crosslinked partially formed acetabular cups with or without annealing, the above specimens were artificially aged by

heating in an oven slowly (~ 0.2°C/min) to 80°C at ambient atmosphere and holding at 80°C for either 20 or 30 days. After artificial aging, the oxidation of aged specimens were examined with FTIR as a function of depth, as described in EXAMPLE 4.

Results and Discussion

After artificial aging, the oxidation of non-annealed material increased with increasing radiation dose (FIGs. 18 and 19). In contrast, annealing at 100°C for 3 days apparently reduced the susceptibility of the material to oxidation, compared to the non-annealed material, as indicated by the low oxidation ratios (FIGs. 18 and 19).

FIG. 20 shows that absent artificial aging, annealing in vacuum at 100°C for 6 days induced only minor oxidation at the surface of the e-beam surface-crosslinked partially formed acetabular cups. The low oxidation profiles of FIGs. 21 and 22 are comparable to that of FIG. 20, even though the partially formed acetabular cups of FIGs. 21 and 22 were subsequently artificially aged at 80°C for 20 and 30 days, respectively. Thus, the oxidation of the annealed e-beam surface-crosslinked partially formed acetabular cups did not increase with artificial aging, which indicates that annealing at 100°C for 6 days substantially reduced the free radicals present in the partially formed acetabular cups.

These results demonstrated that the final shape of acetabular cup can be fabricated from the irradiated-annealed, partially formed cups simply by finish-machining the outer surface. Furthermore, if the minor oxidation at the surface after annealing (FIG. 20) is a concern, the partially formed cups can be made slightly undersized (i.e., slightly smaller I.D. than needed for the final product) prior to irradiation, and the lightly oxidized layer can be removed during the final machining, thereby producing optimal crosslinking at the initial bearing surface. If the inner surface is to be finish-machined, the energy and dose of the crosslinking radiation can be adjusted to produce a thicker crosslinked layer such that the crosslinking profile

that remains after the final machining has the desired shape.

EXAMPLE 8

WEAR TESTING OF CUPS THAT HAVE BEEN SURFACE-CROSSLINKED USING LOW-ENERGY E-BEAM IRRADIATION OR PEROXIDE CROSSLINKING

Materials and Methods

The grade of UHMWPE and details of the methods for producing surface-crosslinked acetabular cups using low-energy e-beam irradiation were described in EXAMPLE 7. A partially formed acetabular cup with 32 mm I.D. (FIG. 12) was machined from the extruded bar and then crosslinked with a 650 KeV e-beam to 5, 10 and 15 Mrad at the surface, and then annealed in a vacuum oven at 100°C for three days. For wear testing, the partially formed acetabular cups were finished-machined into acetabular cups with 32 mm I.D. and 49 mm O.D and wear tested.

For surface chemical crosslinking, details were described in EXAMPLE 6. GUR 1050 UHMWPE powder was placed in a 32 mm I.D. by 50 mm O.D. cup mold and heated to 170°C under 1000 psi for one hour, and then slow-cooled at 2000 psi pressure to below 100°C. A 0.5 mm thick layer of UHMWPE powder mixed with 1 wt% peroxide was placed on the bearing surface, and the cup was heated to 170°C for 2 hours at 1000 psi pressure, then slow-cooled, removed from the mold and then annealed at 80°C in a vacuum oven for 16 hours to reduce residual stresses and stabilize the dimensions. All cups were sterilized with ethylene oxide prior to wear testing. The wear tests were conducted in accordance with the method described in EP 0722973 A1, except as noted below. Three cups each of the four groups were wear tested. Prior to wear testing, the cups were pre-soaked in distilled water for three weeks to minimize additional fluid absorption during the wear test, thereby making the weight loss method for wear measurement more accurate. During the wear test, the cups were enclosed in polyurethane molds and pressed into stainless steel holders. Each holder was

fitted with an acrylic chamber wall to contain the lubricant. The chambers were mounted on the hip simulator wear machine, with each cup bearing against a ball of cobalt-chromium alloy (conventional hip replacement femoral balls were used, with implant-quality surface finish). The ball-cup pairs were subjected to a physiological cyclic load with a peak load of about 2000 Newtons [Paul, J. P., "Forces transmitted by joints in the human body", in Lubrication and Wear in Living and Artificial Human Joints, *Proc Instn Mech Engrs*, **181(3J)**: 8-15 (1967)] and the cups were oscillated against the balls through a bi-axial 46(arc at 68 cycles per minute.

During the wear testing, the bearing surfaces were immersed in bovine blood serum to simulate lubrication in the human body. Sodium azide at 0.2% was added to the serum to retard bacterial degradation, and 20 mM ethylene-diaminetetraacetic acid (EDTA) was added to minimize precipitation of calcium phosphate onto the surface of the balls (McKellop, H. & Lu, B., "Friction and Wear of Polyethylene-metal and Polyethylene-ceramic Hip Prostheses on a Joint Simulator", Transactions of the Fourth World Biomaterials Congress, Berlin, Apr. 1992, p. 118). A PE skirt covered each test chamber to minimize contamination by air-borne particles.

At intervals of 250,000 cycles, the cups were removed from the machine, rinsed, inspected under light microscopy and replaced in fresh lubricant. At intervals of 500,000 cycles, the cups were removed, cleaned, dried and weighed to indicate the amount of wear. After inspection under light microscopy, the cups were replaced on the wear machine with fresh lubricant and testing was continued to a total of five million cycles. One million cycles are approximately the equivalent of one year's walking activity of a typical patient.

Three control cups of each material were immersed in serum and cyclically loaded on a separate frame, but without oscillation. The mean weight gain of the three control cups was added to the weight loss of each wear cup to correct for

masking of the wear by fluid absorption. The mean weight loss of the wear cups (after soak correction) and the standard deviation were calculated for each of the four types of materials at each weighing interval. The wear rate of each cup was calculated by applying linear regression to the wear data for the entire five million cycles. The mean wear rates and standard deviations were also calculated for each type of material.

Results and Discussion

The wear rates were lower for the cups with the higher amount of crosslinking. That is, wear decreased with increasing radiation dose (FIG. 23 and Table 1, below). In addition, for a given crosslinking dose, the wear rates decreased (FIG. 23, Table 1) as wear penetrated from the surface into the maximally crosslinked subsurface region (FIG. 14). For example, from 2 to 5 million cycles, the wear rates for the 5, 10 and 15 Mrad cups averaged 21.9, 13.8 and 7.6 milligram per million cycles, respectively and, for the surface peroxide-crosslinked cups, 12.7 milligram per million cycles, i.e., comparable to that of the 10 Mrad cups over the same interval.

Table 1

Material	Cup #	0 - 5 Million Cycles		2 - 5 Million Cycles	
		Wear Rate (mg /million cycles)	Mean Wear Rate ± Std Deviation	Wear Rate (mg /million cycles)	Mean Wear Rate ± Std Deviation
5 Mrad	1	24.85	23.89 ± 2.35	23.37	21.91 ± 2.32
	2	21.21		19.24	
	3	25.61		23.13	
10 Mrad	1	14.24	14.62 ± 0.44	13.56	13.79 ± 0.24
	2	15.11		13.78	
	3	14.53		14.05	
15 Mrad	1	7.42	8.56 ± 1.04	6.33	7.57 ± 1.07
	2	9.45		8.23	
	3	8.80		8.13	
Peroxide-crosslinked	1	17.18	15.50 ± 1.81	14.48	12.69 ± 1.81
	2	13.59		10.86	
	3	15.75		12.71	

EXAMPLE 9

OXIDATION-RESISTANT PEROXIDE CROSSLINKED UHMWPE

Materials and Methods

The grades of the UHMWPE and the peroxide used in this example, and details of mixing the UHMWPE powder with peroxide, were described in EXAMPLE 2. The peroxide concentration in the present study was 2 weight percent. The peroxide-mixed UHMWPE powder was placed in a rectangular mold (dimension 8.8 x 3.7 x 2.8 cm), cold-pressed at room temperature and 2000 psi pressure on the powder for 10 minutes, and then heated to 170°C under a 1000 psi pressure on the powder for 2 hours. The 8 mm thick sample was then slowly cooled in the mold to room temperature. A subset of 8 mm thick blocks (2 weight percent peroxide) was then melted at 153°C in a vacuum oven for 5 hours and subsequently slow-cooled in the oven to room temperature.

To examine the oxidation resistance of the peroxide-crosslinked UHMWPE with or without remelting, the above specimens were artificially aged by heating in an oven slowly (~ 0.2°C/min) to 80°C at ambient atmosphere and holding at 80°C for 30 days. After artificial aging, the degree of oxidation of the specimens was measured as a function of depth from the surface using FTIR as described in EXAMPLE 4.

Results and Discussion

After artificial aging, there was substantial oxidation in the surface region of the non-remelted material (FIG. 24). In contrast, artificial aging induced only minor oxidation in the remelted material, with a local peak about 2 mm below the surface, as indicated by the low oxidation ratios (FIG. 24). That is, remelting at 153°C for 5 hours reduced the susceptibility of the material to oxidation as induced by artificial aging. This indicated that remelting of a surface peroxide-crosslinked acetabular cup will improve its resistance to oxidation over time in-vivo. In the case of an acetabular cup, a partially formed acetabular

cup can be fabricated with the inner diameter slightly undersized than needed for the final product, and this partially formed acetabular cup can be finish machined after crosslinking and remelting, in order to correct for any shrinkage and/or distortion due to remelting. A comparable process can be used for components for the knee, shoulder or ankle or other joints. In such cases, the initial thickness of the chemically crosslinked layer can be increased, such that the desired crosslinking profile remains after the final component is fabricated from the partially formed acetabular cup.

All publications and patent applications mentioned in this Specification are herein incorporated by reference to the same extent as if each of them had been individually indicated to be incorporated by reference.

Although the foregoing invention has been described in some detail by way of illustration and example for purposes of clarity and understanding, it will be obvious that various modifications and changes which are within the skill of those skilled in the art are considered to fall within the scope of the appended claims. Future technological advancements which allow for obvious changes in the basic invention herein are also within the claims.

We claim:

1. A surface-crosslinked implant comprising a polyethylene bearing surface having a maximum gel content of from about 80 to about 100% within the bearing surface, the gel content gradually decreasing to about 50% of the maximum gel content at about 0.5 to about 2 mm from the bearing surface, and tapering to nearly zero by about 2 to about 2.5 mm from the bearing surface; the remainder of the implant remains uncrosslinked.

2. A method for improving the wear resistance of a bearing surface of an implant, wherein said bearing surface comprises polyethylene, the method comprises the step of subjecting the bearing surface, of the implant which is fully or partially formed, to electron-beam radiation to crosslink the bearing surface, while the remainder of the implant that is not part of the bearing surface is not subjected to the electron-beam radiation and, therefore, remains uncrosslinked.

3. The method of claim 2, wherein the irradiated fully or partially formed implant is further subjected to one or more of the following steps: (1) pressurization in hydrogen to reduce or eliminate residual free radicals generated by the irradiation, (2) annealing or remelting to reduce or eliminate residual free radicals generated by the irradiation, (3) shaping the partially formed implant into its final shape, and (4) treating with ethylene oxide to reduce or eliminate residual free radicals generated by the irradiation.

4. The method of claim 3, wherein the shaping step comprises removing the most oxidized outer layer of the bearing surface of the irradiated implant.

5. A method for improving the wear resistance of a bearing surface of an implant, wherein said bearing surface comprises polyethylene, the method comprising the steps of crosslinking the bearing surface of a fully or partially formed implant with a free radical generating chemical, the remainder of the fully or partially formed implant that is not part of the bearing surface remains uncrosslinked.

6. The method of claim 5, wherein the crosslinked fully or partially formed implant is further subjected to one or more of the following steps: (1) reducing or removing the residual chemicals resulting from the crosslinking process, (2) annealing at a temperature and for a time sufficient to stabilize its size and shape, (3) remelting to improve its oxidation resistance, and (4) shaping into its final shape.

7. The method of claim 6, wherein the free radical generating agent is a peroxide.

8. The method of claim 6, wherein step (1) comprises soaking the crosslinked fully or partially formed implant in a solvent to remove the residual chemicals resulting from the crosslinking process.

9. The method of claim 6, wherein the shaping step comprises removing the outer most oxidized layer from the crosslinked fully or partially formed implant.

10. An implant or polyethylene produced by any of the foregoing methods of claims 2 to 9.

11. A polyethylene crosslinked on its surface layer, such crosslinking gradually decreasing to nearly zero in the interior of the polyethylene, the crosslinking is achieved by electron beam radiation or chemical means.

12. An implant comprising the polyethylene of Claim 11.

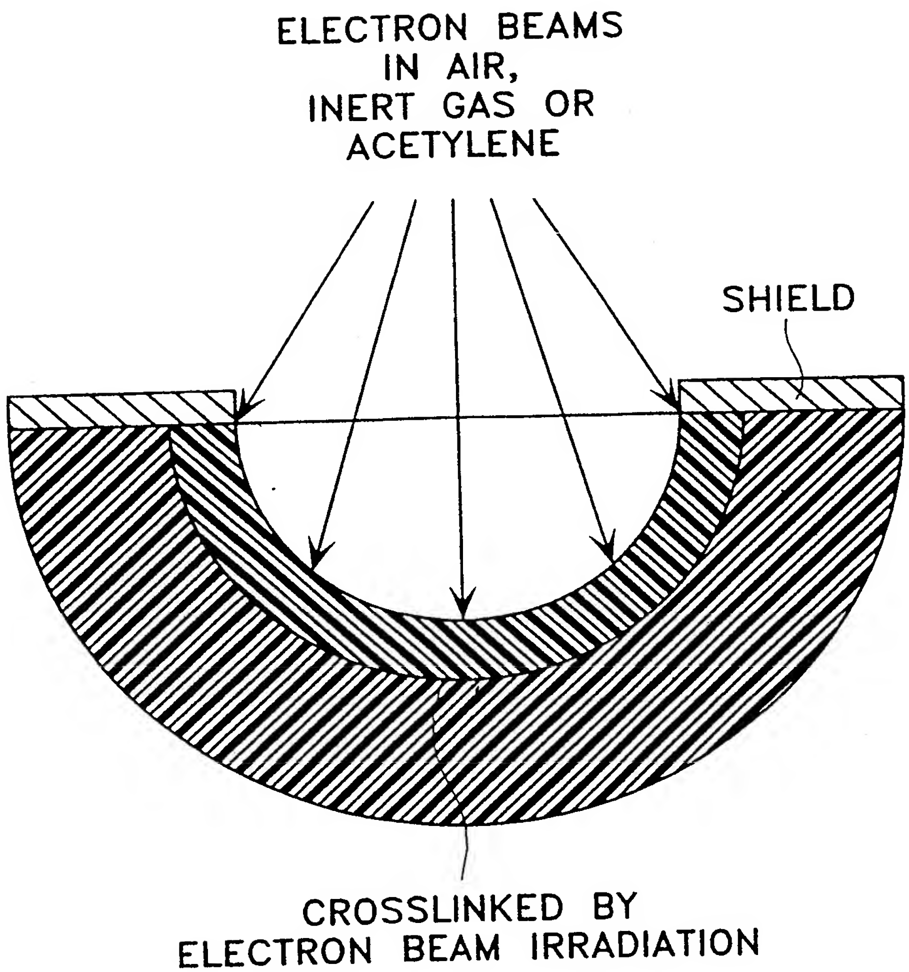

ELECTRON BEAMS
IN AIR,
INERT GAS OR
ACETYLENE
SHIELD
CROSSLINKED BY
ELECTRON BEAM IRRADIATION

FIG. 1

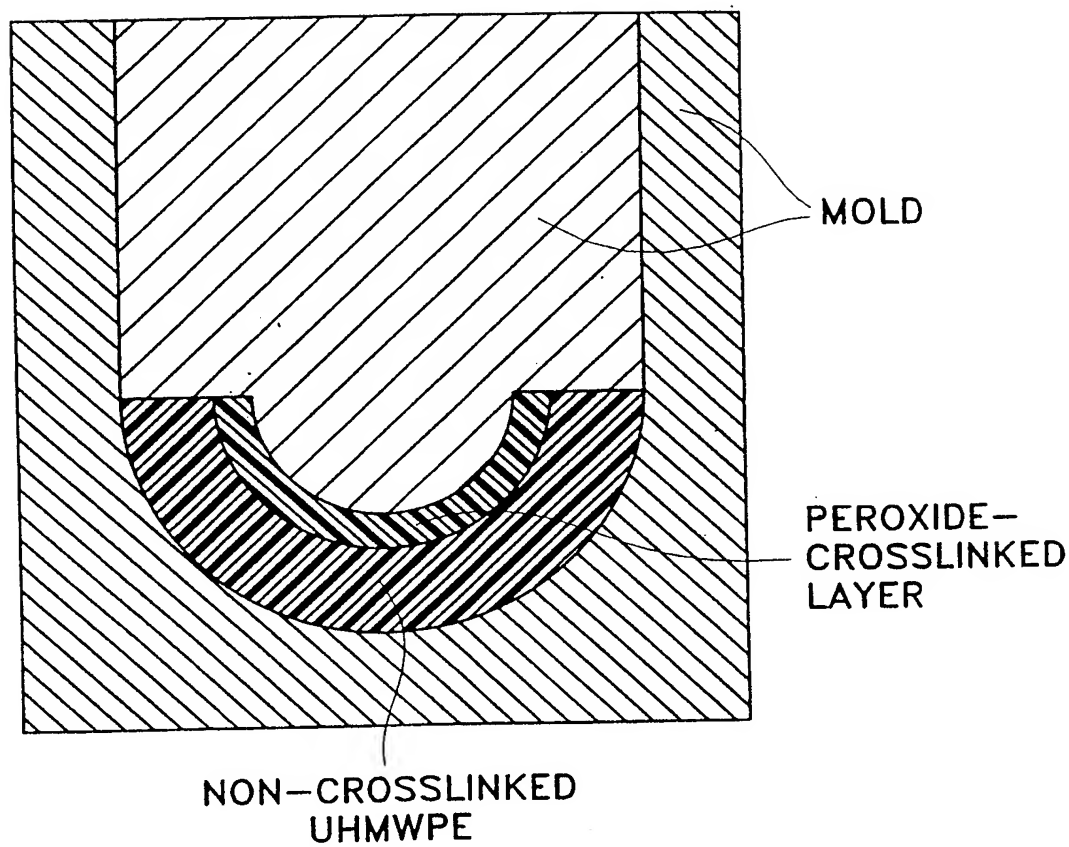


FIG. 2

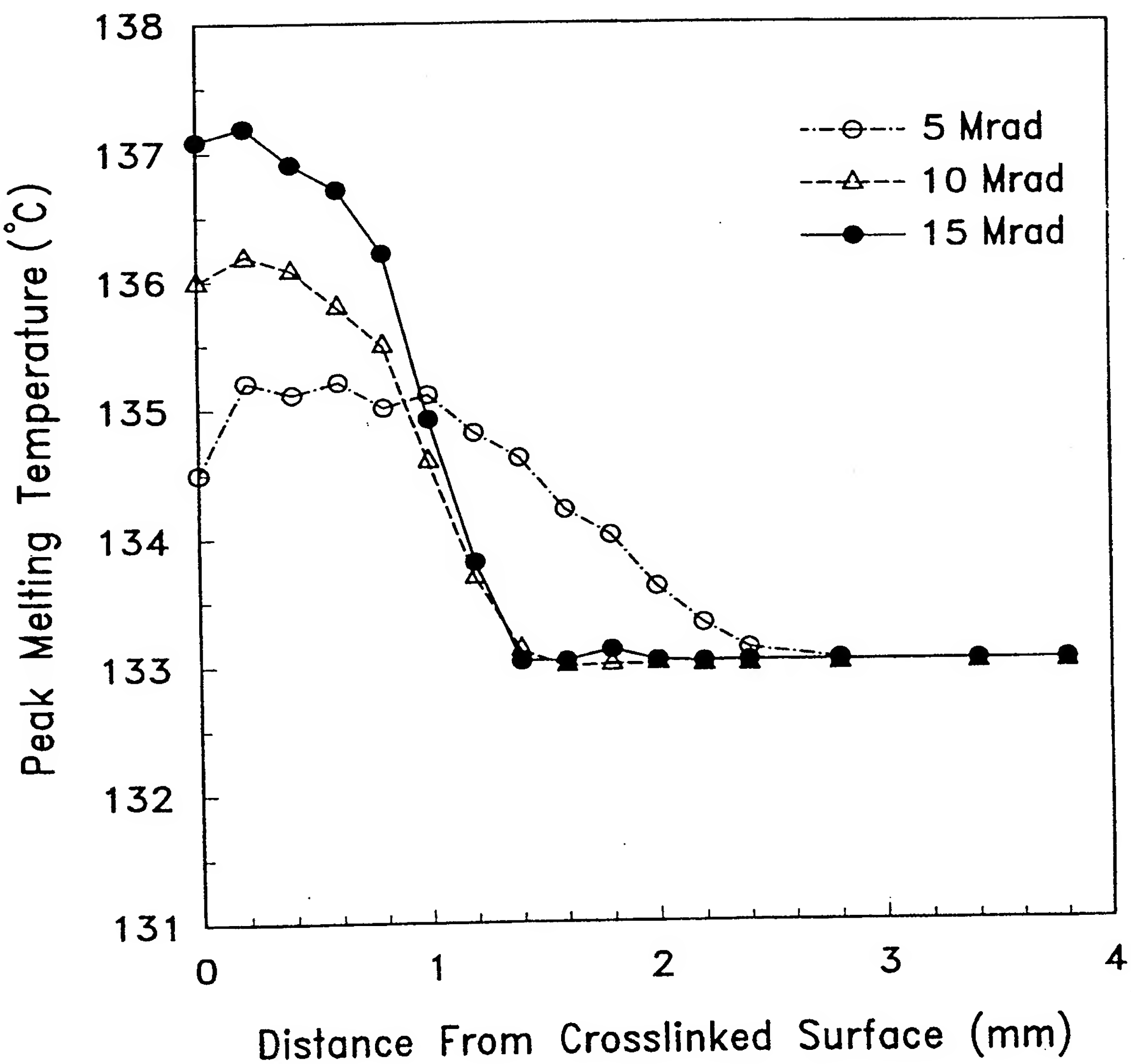

138
137
136
135
134
133
132
131
Peak Melting Temperature (°C)
0
1
2
3
4
Distance From Crosslinked Surface (mm)
5 Mrad
10 Mrad
15 Mrad

FIG. 3

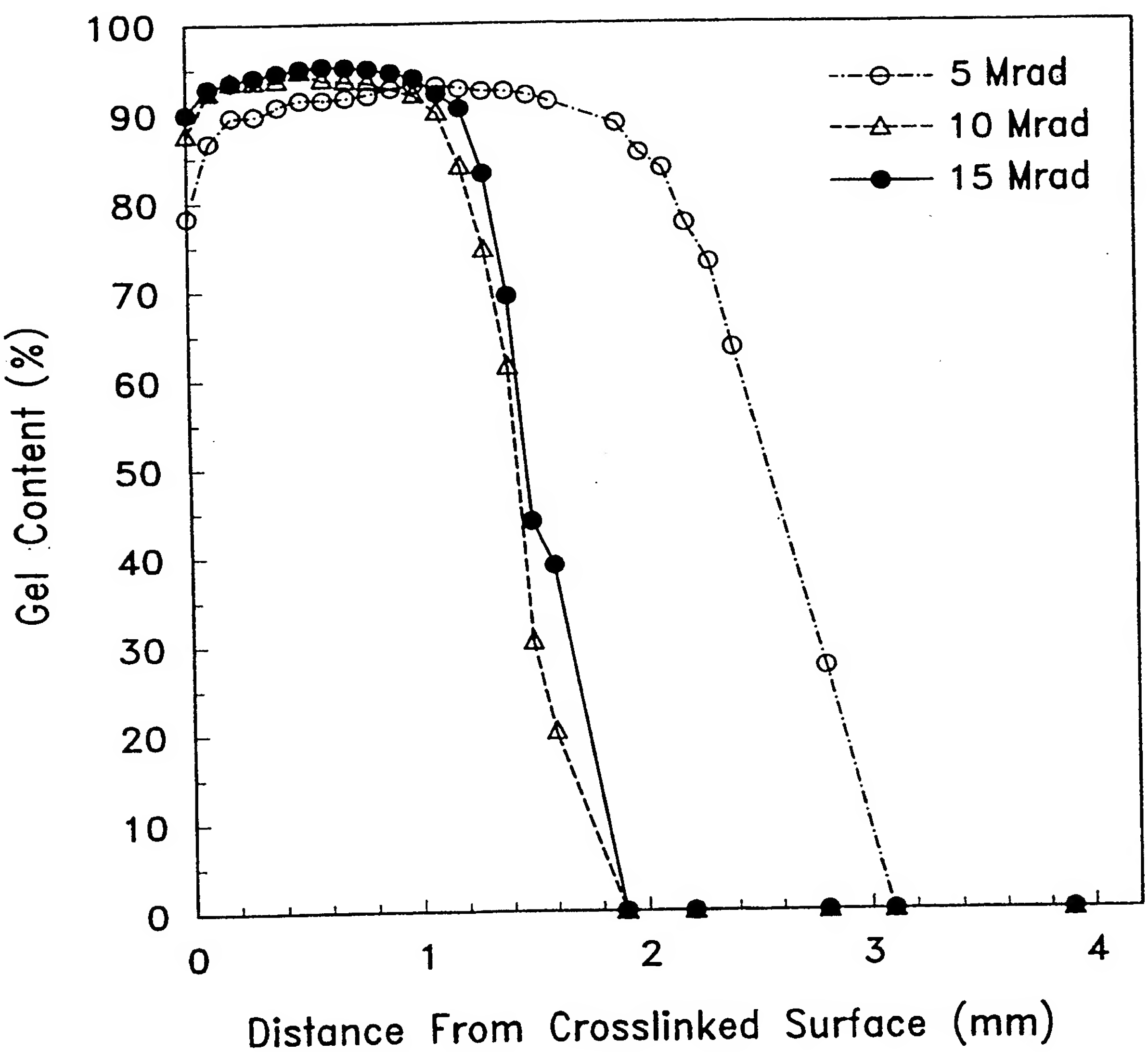
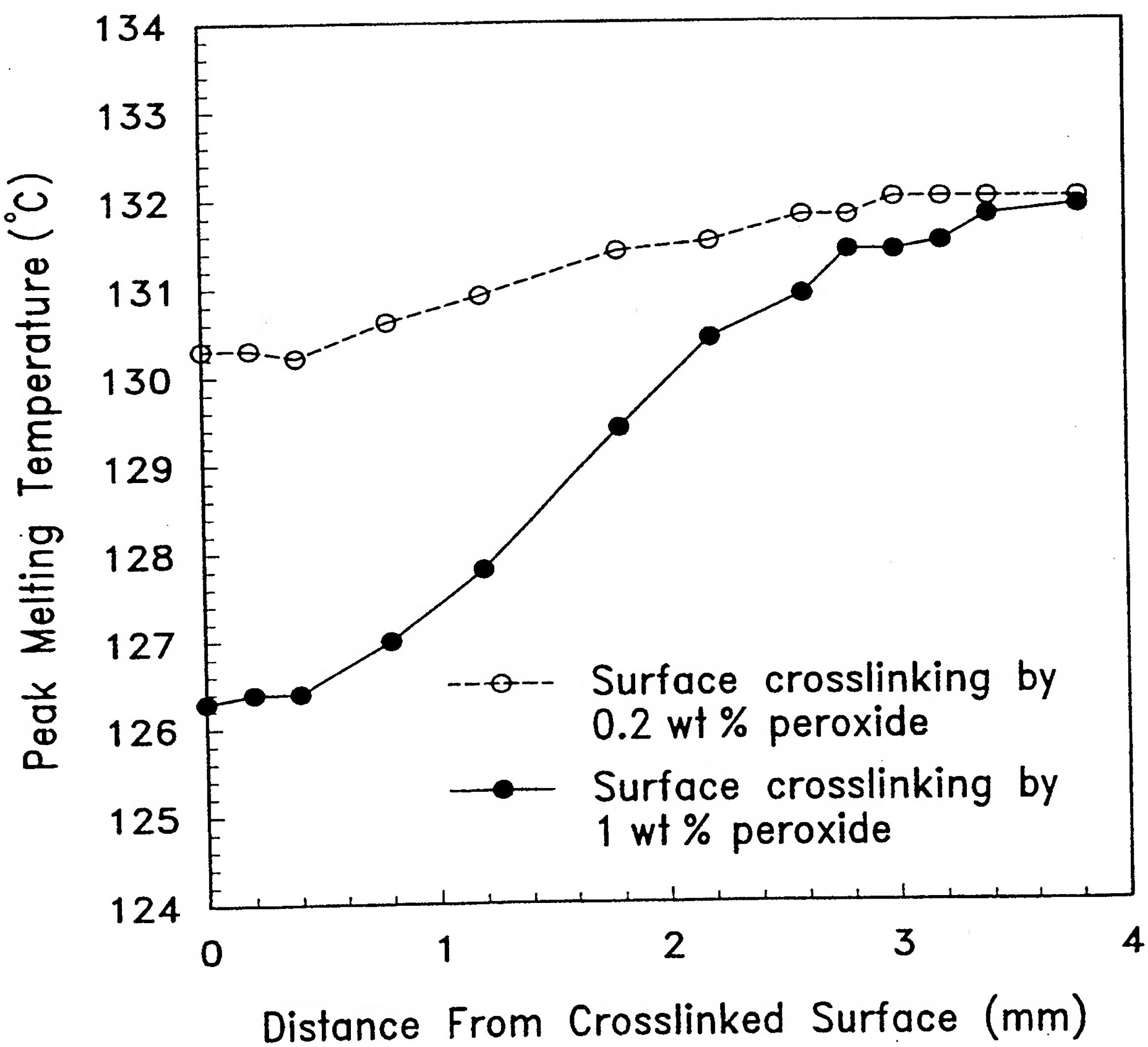

100
90
80
70
60
50
40
30
20
10
0
Gel Content (%)
0
1
2
3
4
Distance From Crosslinked Surface (mm)
5 Mrad
10 Mrad
15 Mrad

FIG. 4



134
133
132
131
130
129
128
127
126
125
124
Peak Melting Temperature (°C)
0
1
2
3
4
Distance From Crosslinked Surface (mm)
Surface crosslinking by 0.2 wt % peroxide
Surface crosslinking by 1 wt % peroxide

FIG. 5

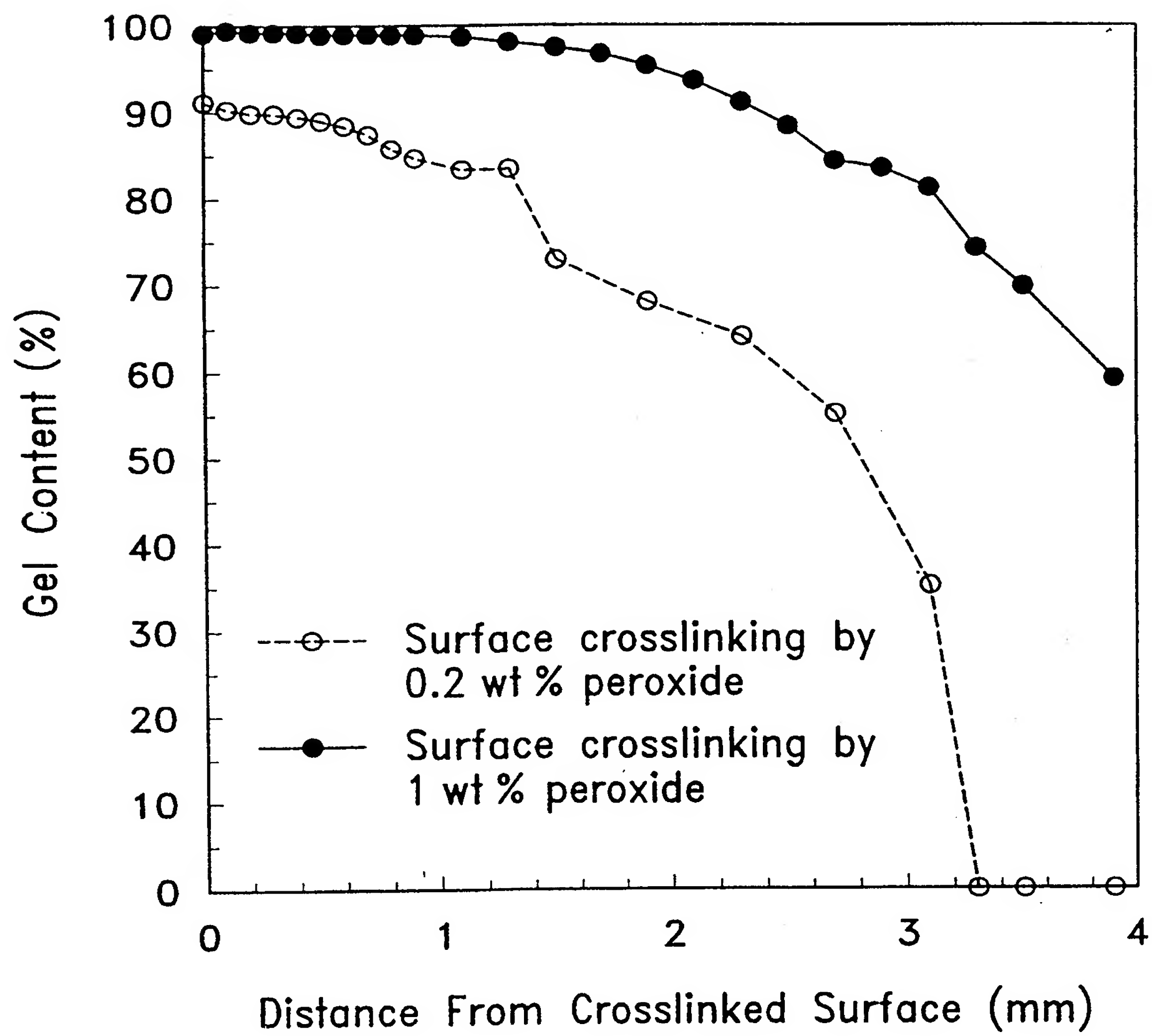
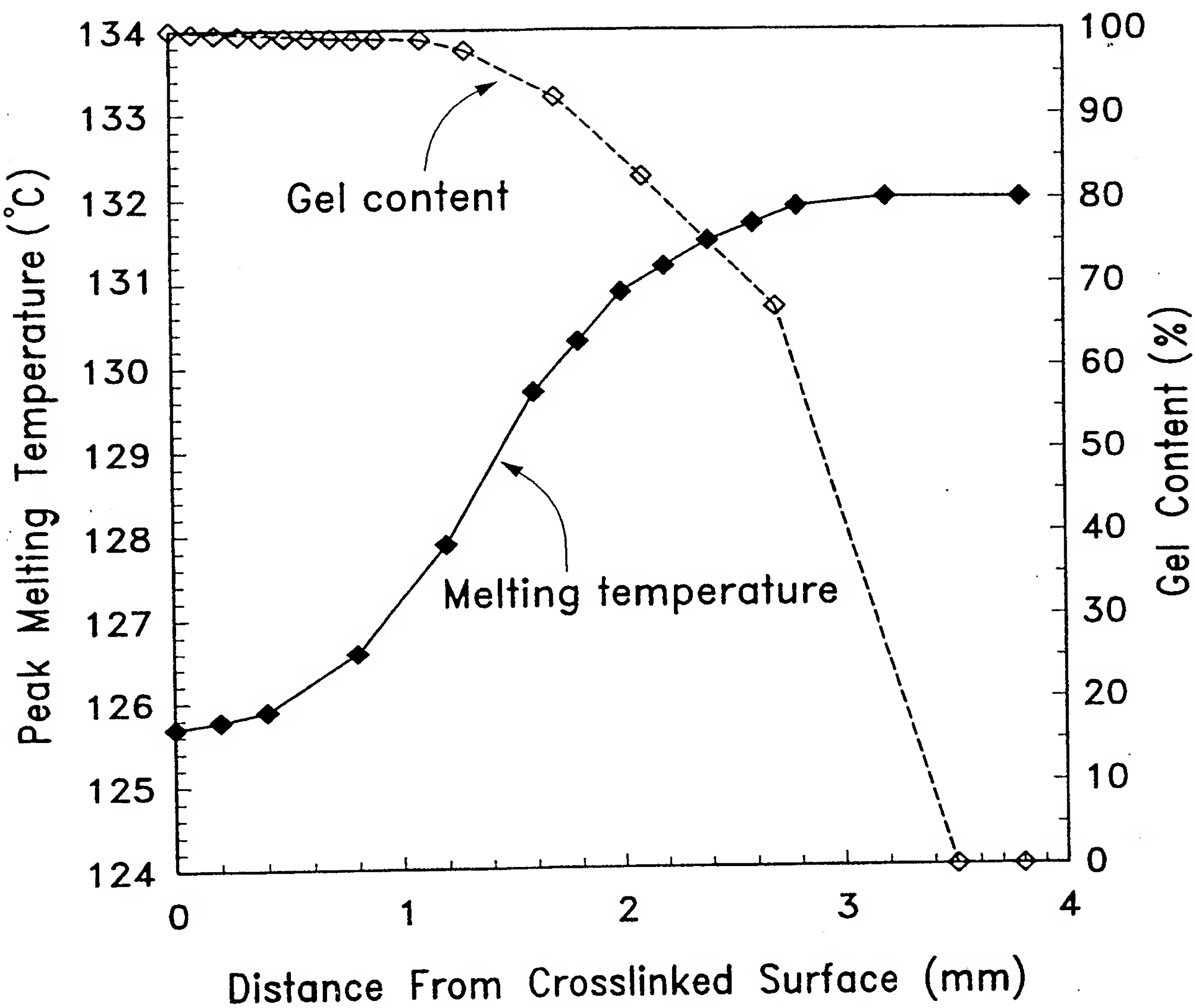
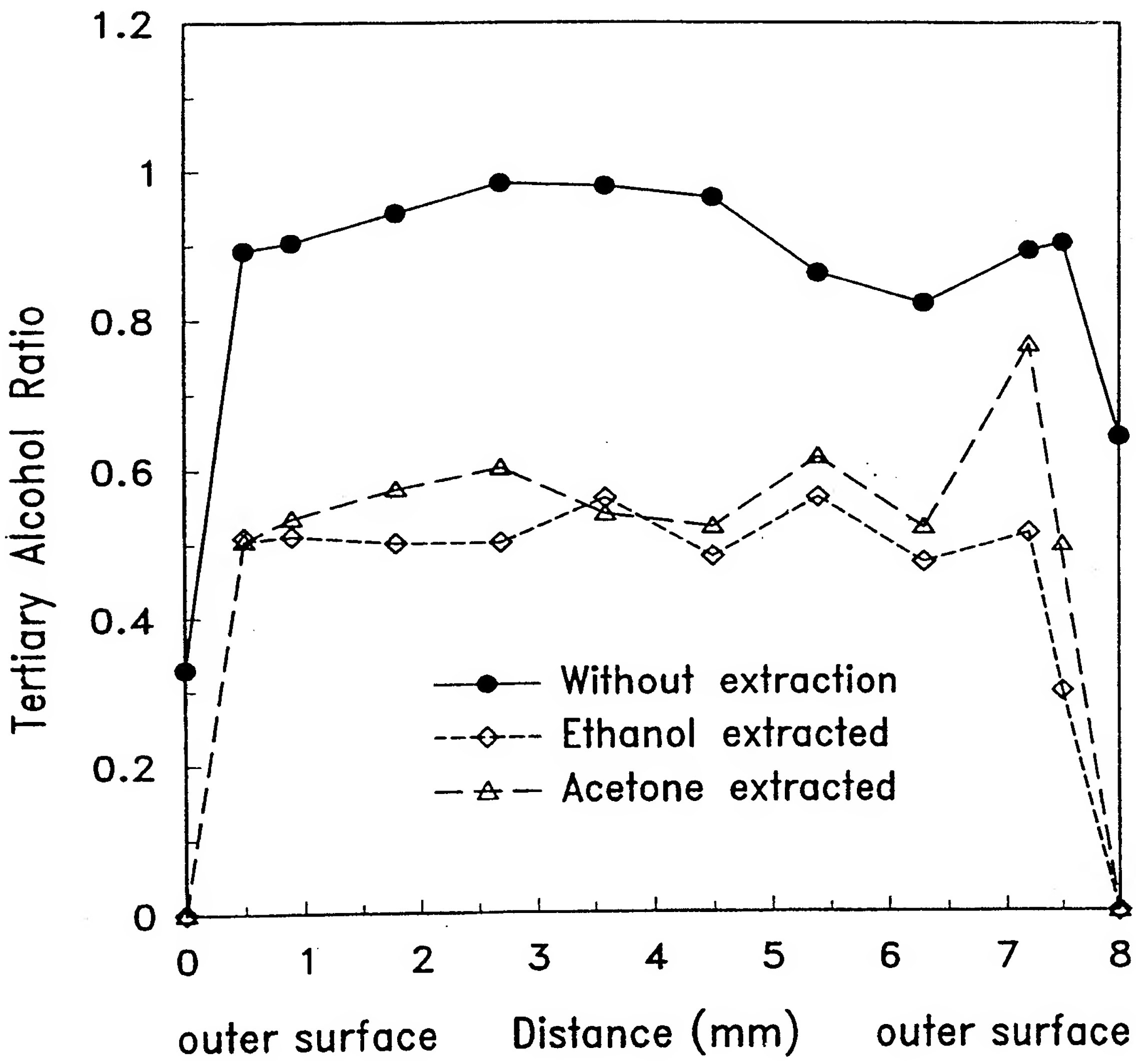

Gel Content (%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
Distance From Crosslinked Surface (mm)
Surface crosslinking by 0.2 wt % peroxide
Surface crosslinking by 1 wt % peroxide

FIG. 6



134
133
132
131
130
129
128
127
126
125
124
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
Gel content
Melting temperature
Peak Melting Temperature (°C)
Gel Content (%)
Distance From Crosslinked Surface (mm)

FIG. 7



1.2
1
0.8
0.6
0.4
0.2
0
Tertiary Alcohol Ratio
Without extraction
Ethanol extracted
Acetone extracted
0
1
2
3
4
5
6
7
8
outer surface
Distance (mm)
outer surface

FIG. 8

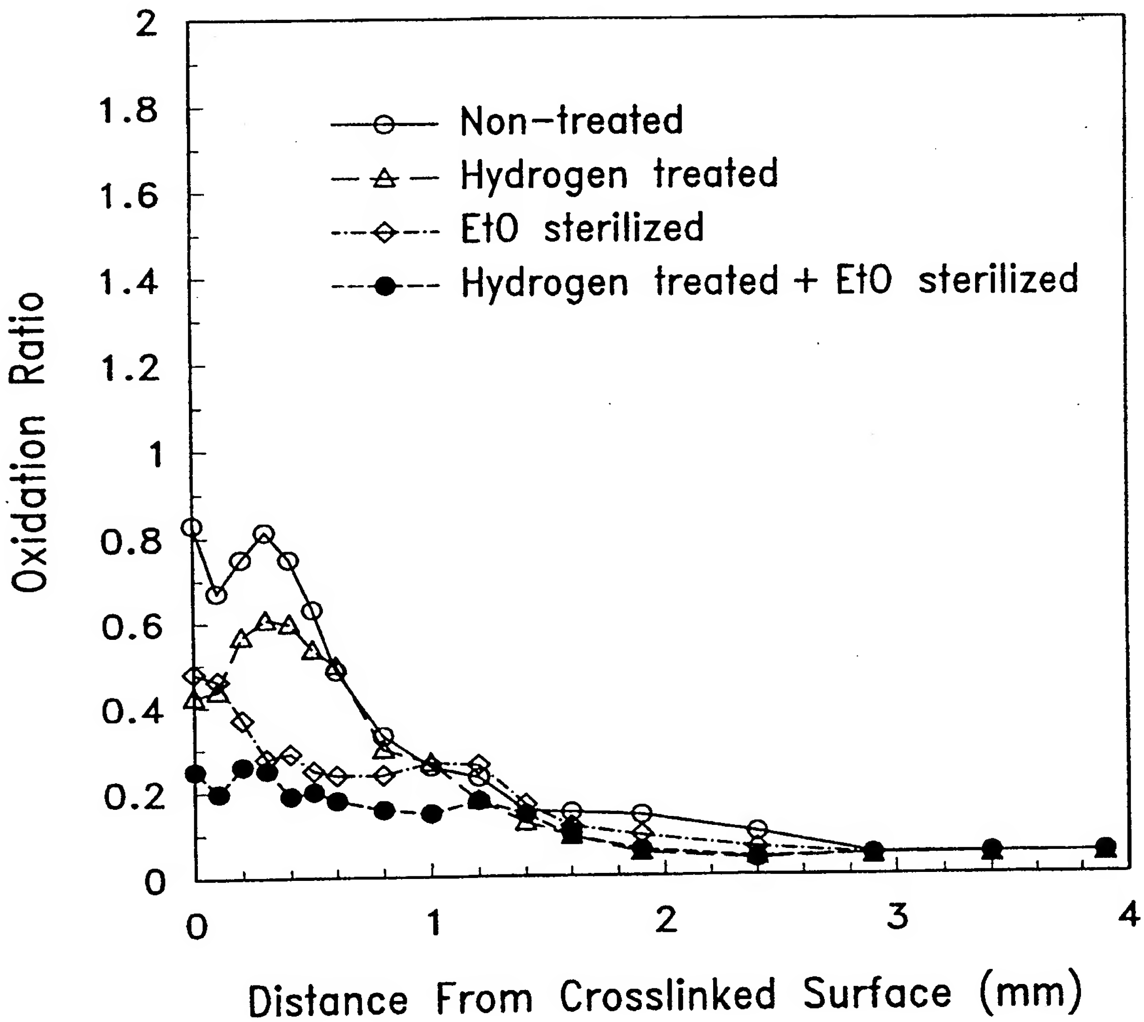
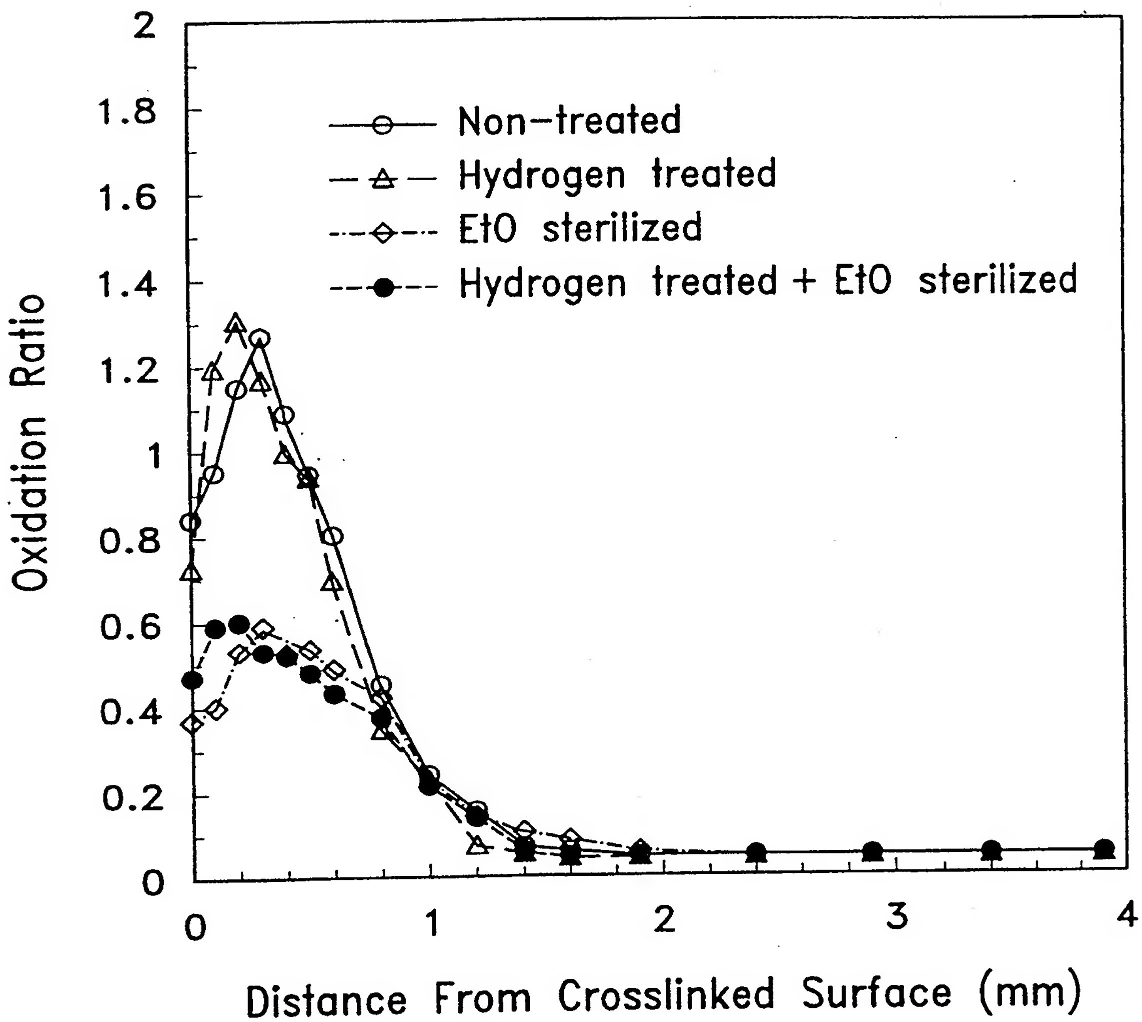
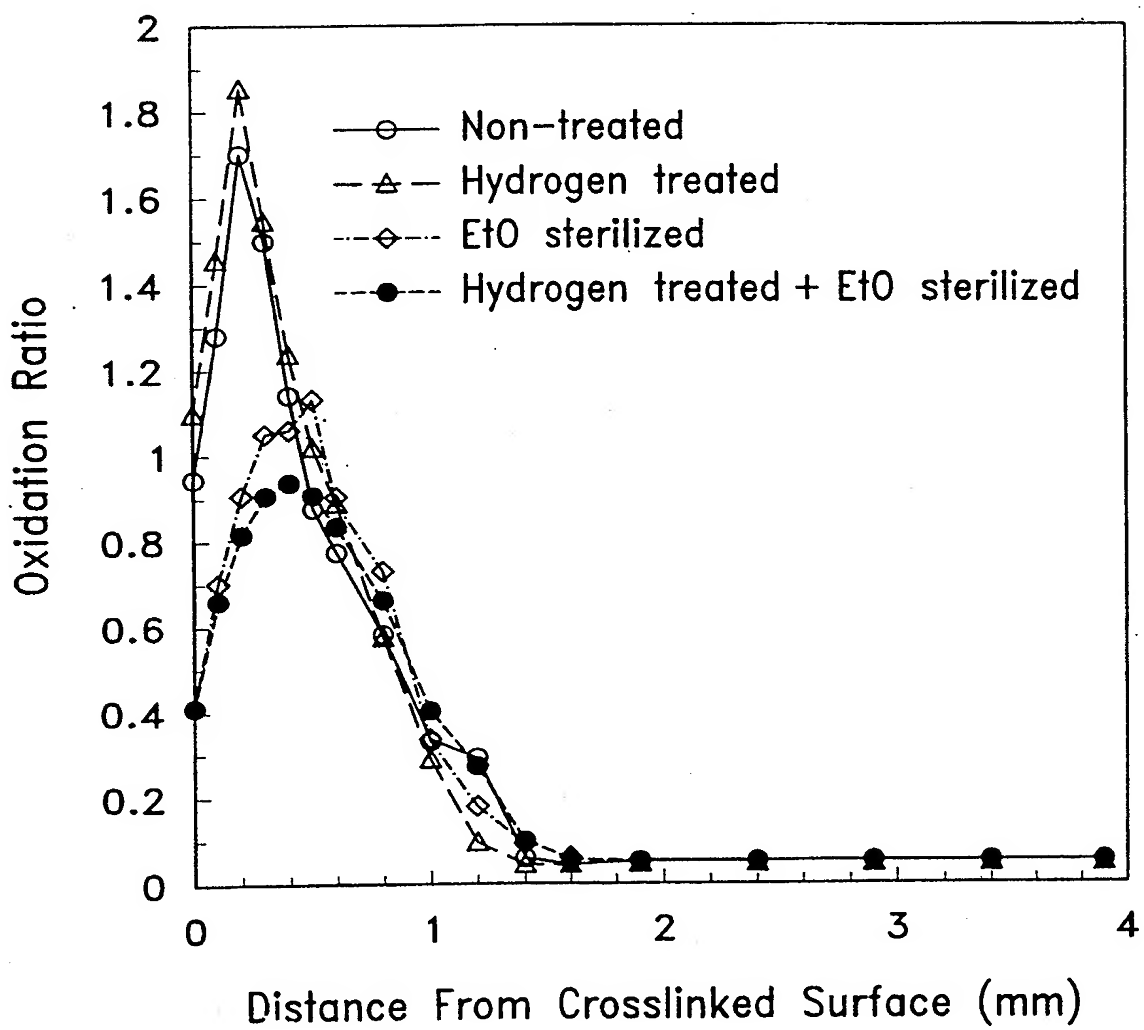

Oxidation Ratio
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
Distance From Crosslinked Surface (mm)
Non-treated
Hydrogen treated
EtO sterilized
Hydrogen treated + EtO sterilized

FIG. 9



Oxidation Ratio
Distance From Crosslinked Surface (mm)
Non-treated
Hydrogen treated
EtO sterilized
Hydrogen treated + EtO sterilized
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
1
2
3
4

FIG. 10



Non-treated
Hydrogen treated
EtO sterilized
Hydrogen treated + EtO sterilized
Oxidation Ratio
Distance From Crosslinked Surface (mm)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
1
2
3
4

FIG. 11

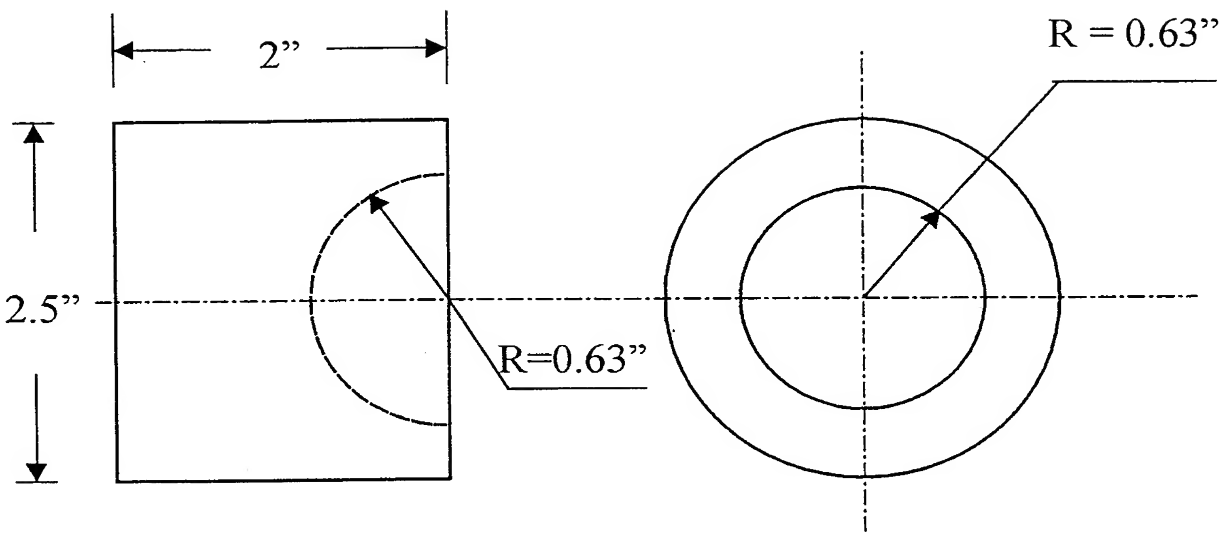


FIG. 12

Fig. 13

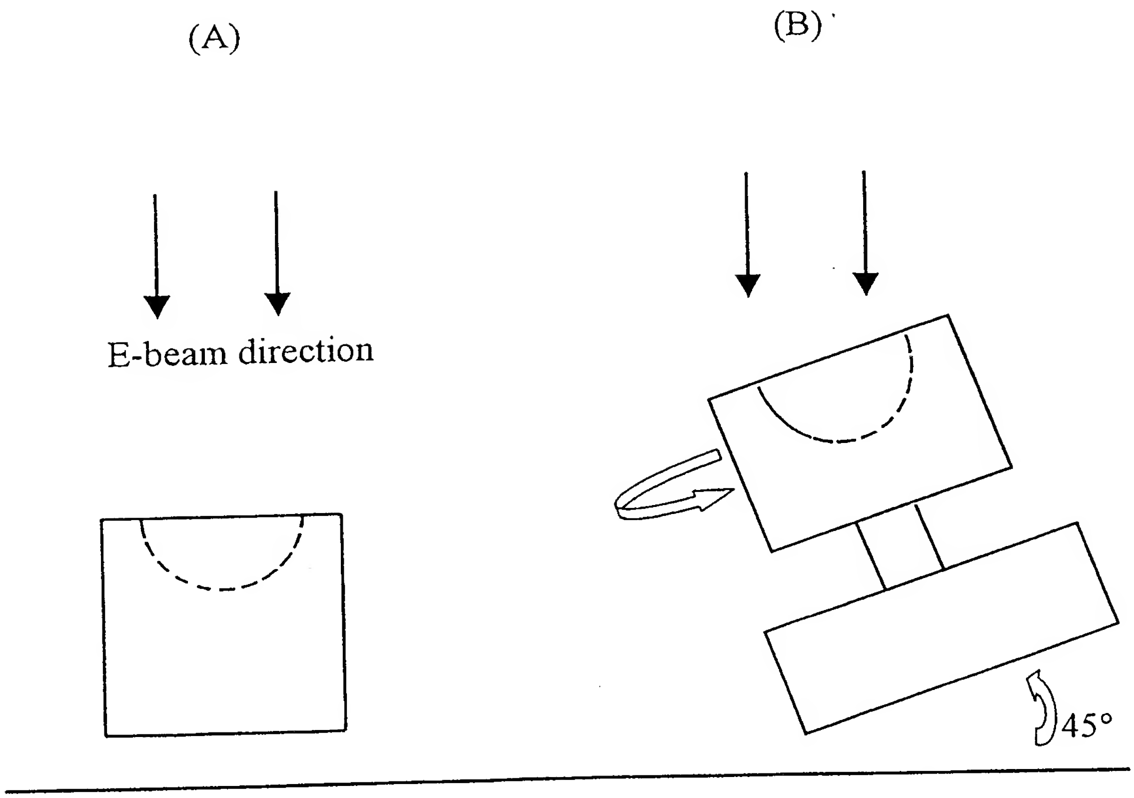
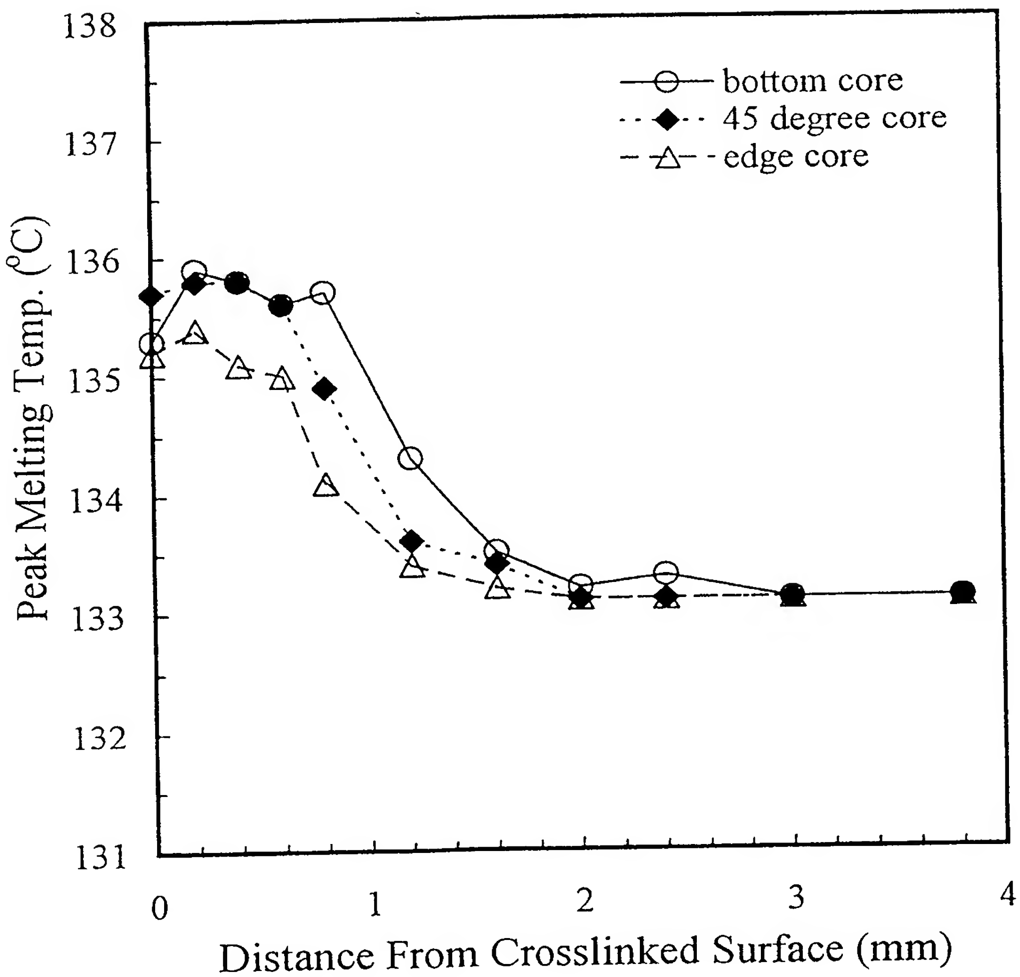


Fig. 14



bottom core
45 degree core
edge core
Peak Melting Temp. (°C)
138
137
136
135
134
133
132
131
0
1
2
3
4
Distance From Crosslinked Surface (mm)

Fig. 15

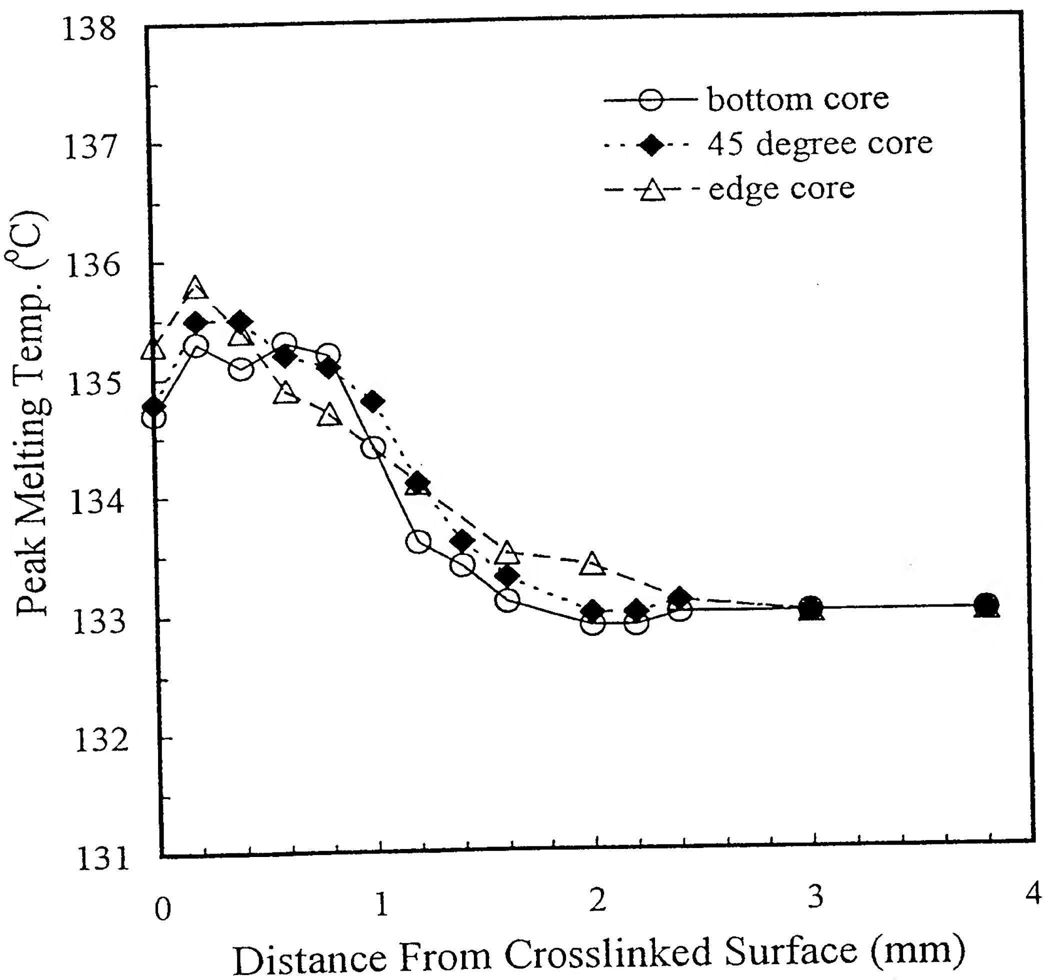

138
137
136
135
134
133
132
131
Peak Melting Temp. (°C)
bottom core
45 degree core
edge core
0
1
2
3
4
Distance From Crosslinked Surface (mm)

Fig. 16

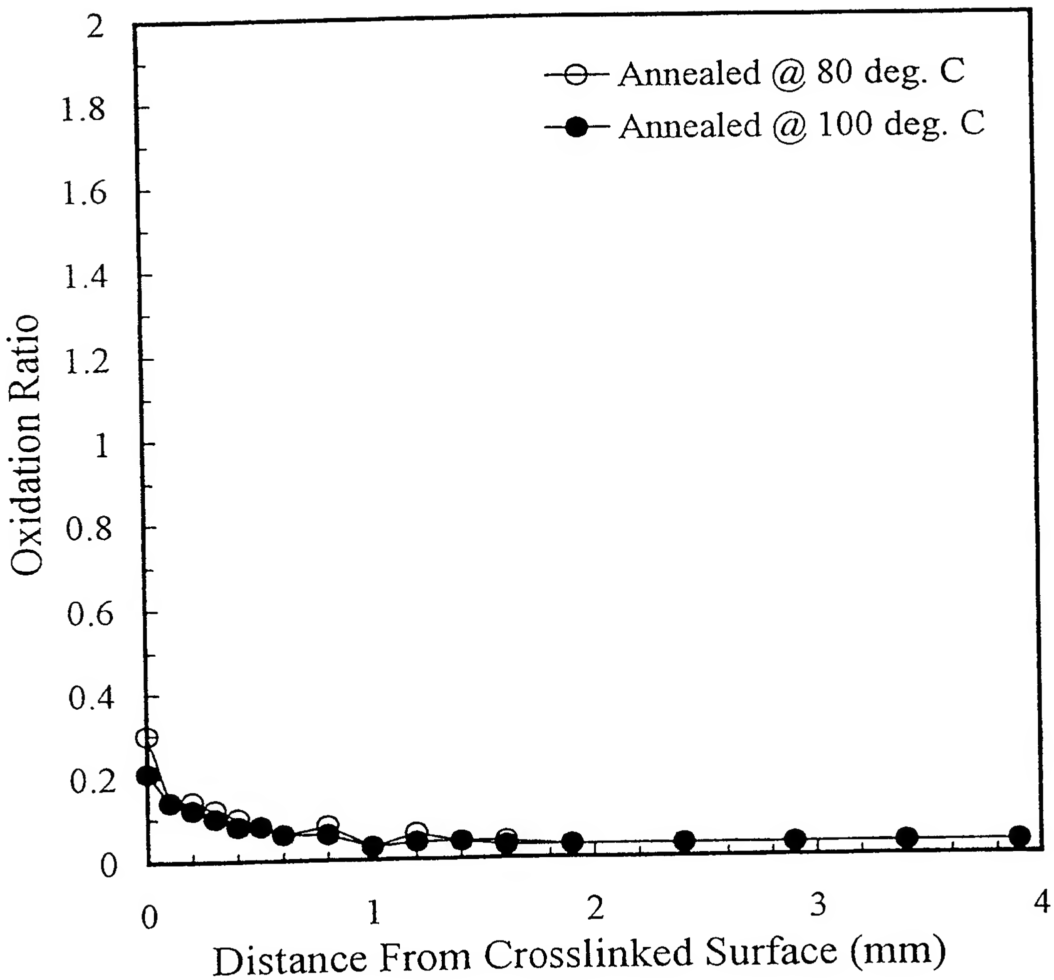

Annealed @ 80 deg. C
Annealed @ 100 deg. C
Oxidation Ratio
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
Distance From Crosslinked Surface (mm)

Fig. 17

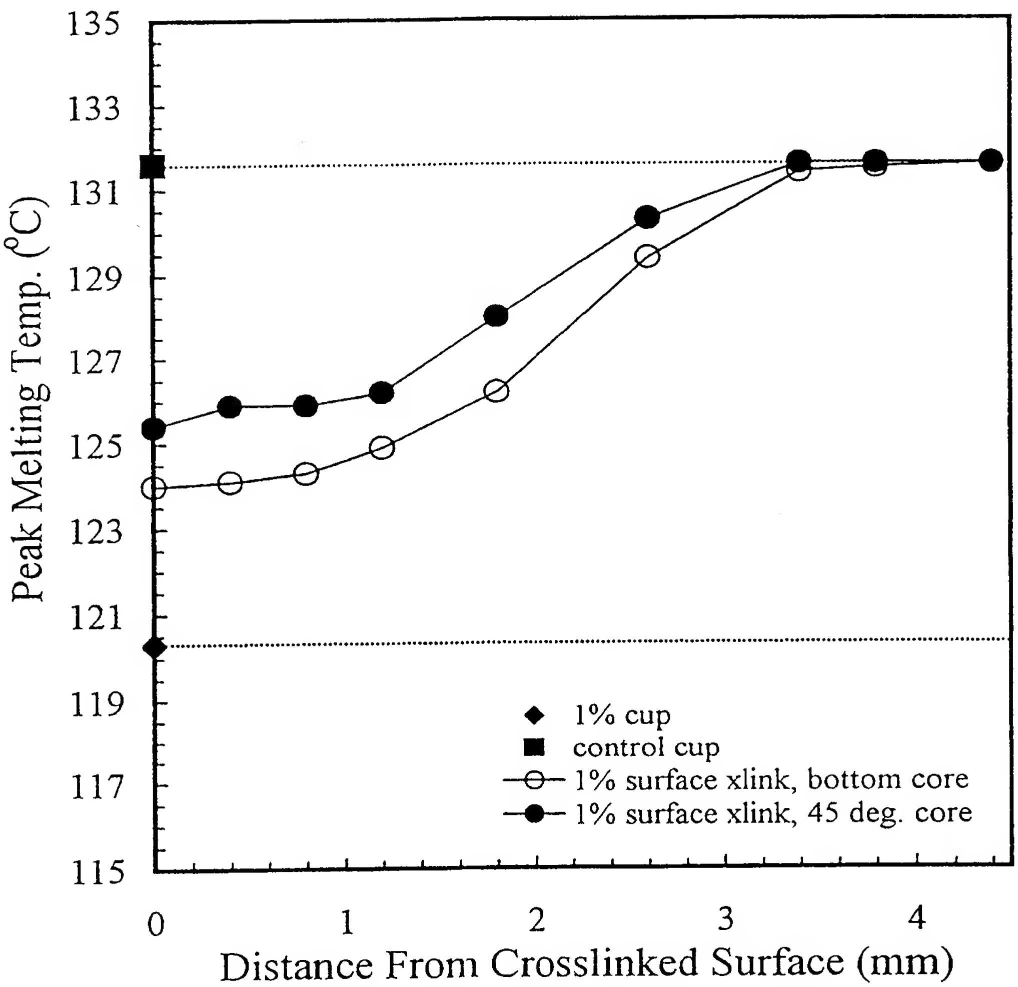

135
133
131
129
127
125
123
121
119
117
115
Peak Melting Temp. (°C)
0
1
2
3
4
Distance From Crosslinked Surface (mm)
1% cup
control cup
1% surface xlink, bottom core
1% surface xlink, 45 deg. core

Fig. 18

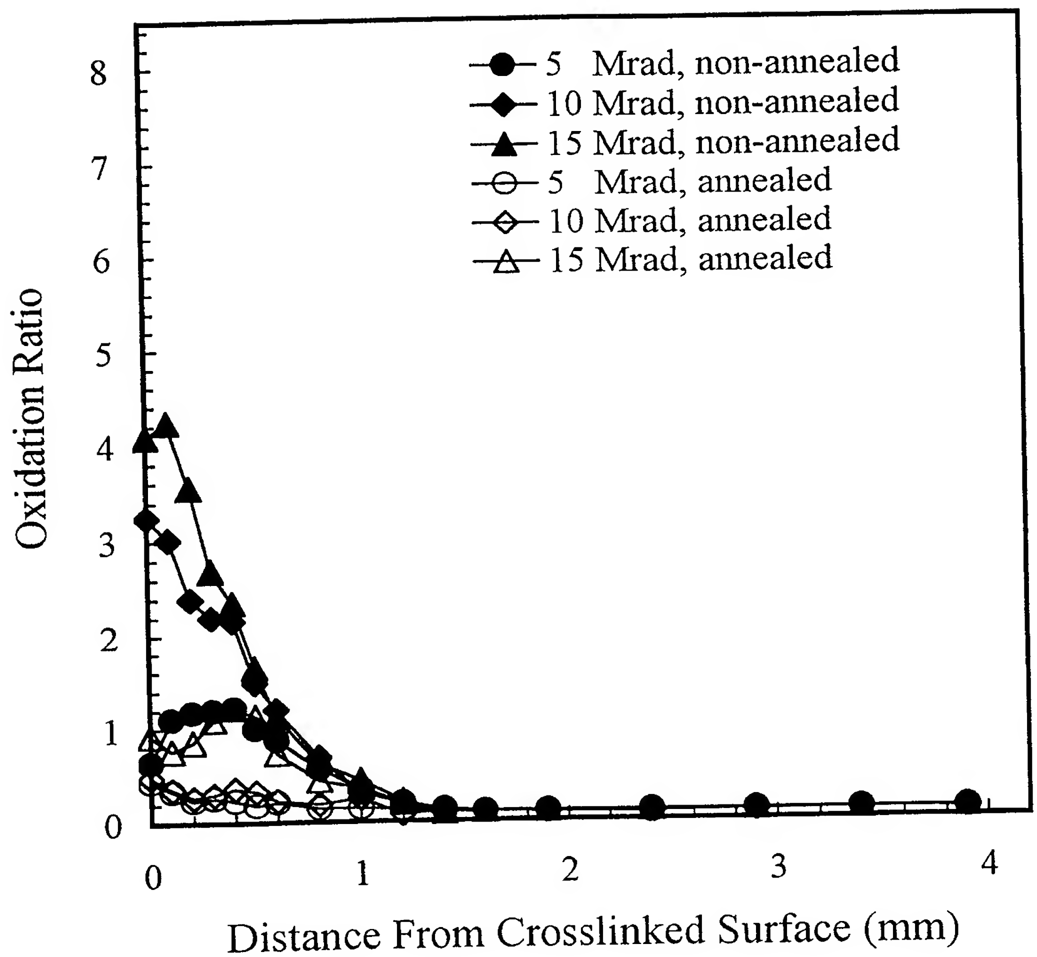

5 Mrad, non-annealed
10 Mrad, non-annealed
15 Mrad, non-annealed
5 Mrad, annealed
10 Mrad, annealed
15 Mrad, annealed
Oxidation Ratio
0
1
2
3
4
5
6
7
8
0
1
2
3
4
Distance From Crosslinked Surface (mm)

Fig. 19

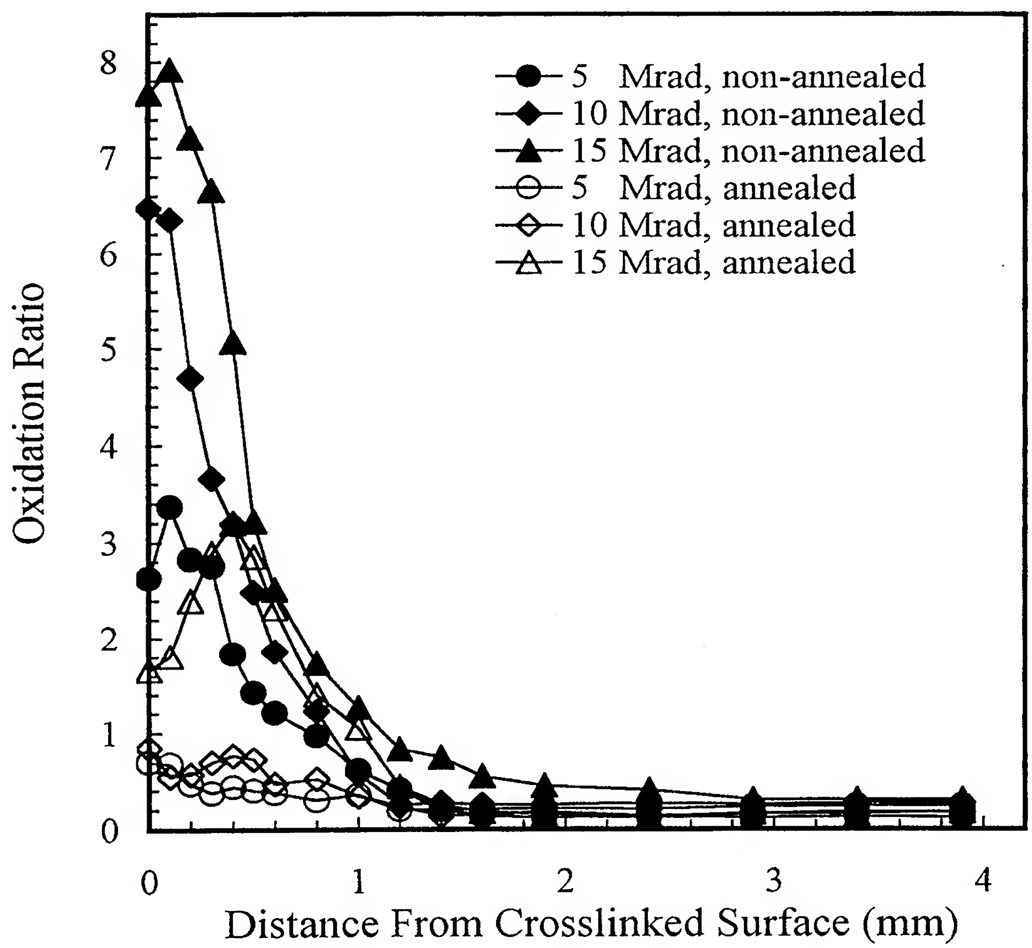
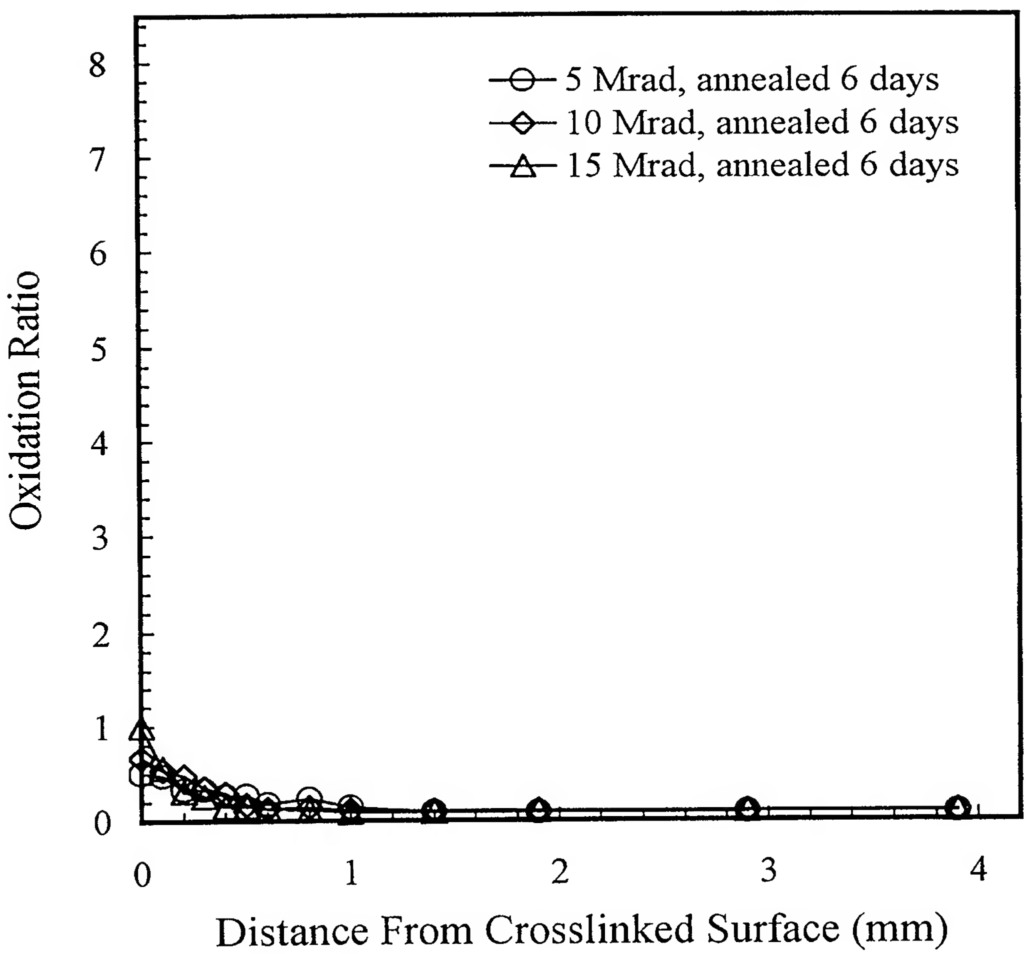
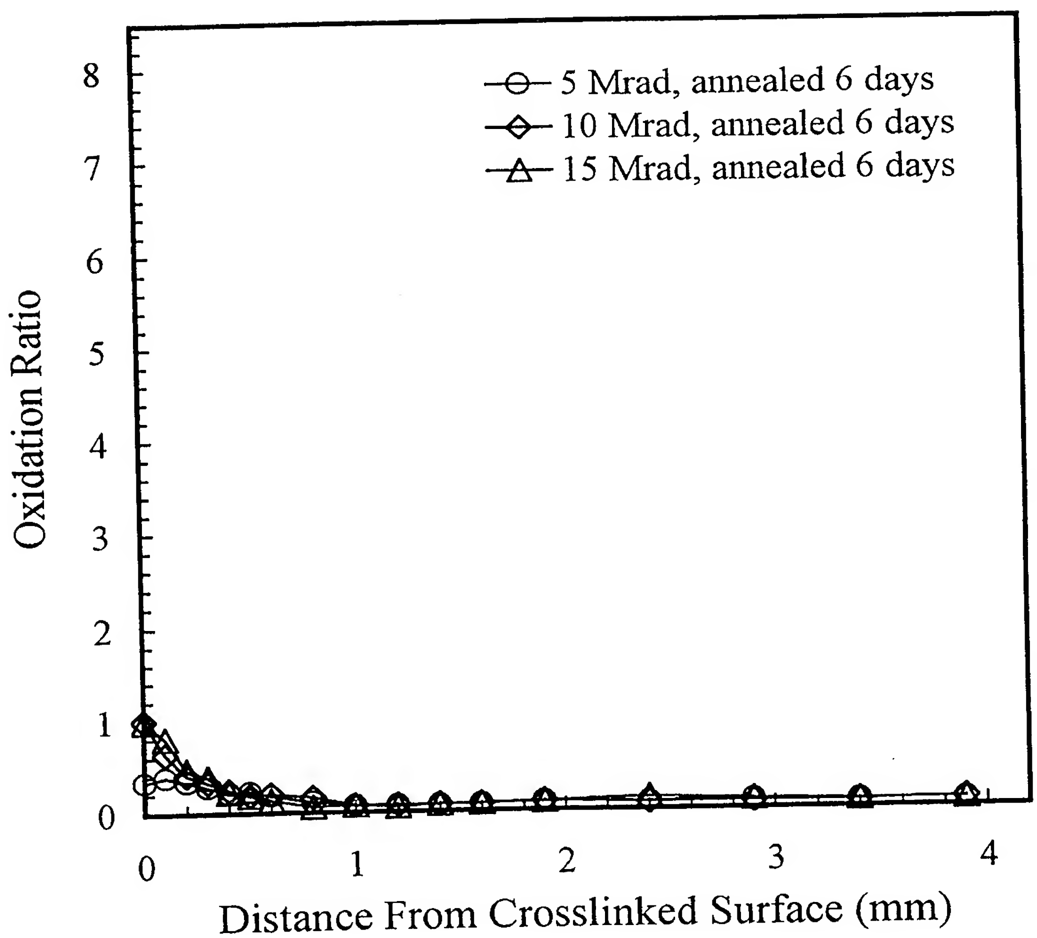

5 Mrad, non-annealed
10 Mrad, non-annealed
15 Mrad, non-annealed
5 Mrad, annealed
10 Mrad, annealed
15 Mrad, annealed
Oxidation Ratio
0
1
2
3
4
5
6
7
8
0
1
2
3
4
Distance From Crosslinked Surface (mm)

Fig. 20



5 Mrad, annealed 6 days
10 Mrad, annealed 6 days
15 Mrad, annealed 6 days
Oxidation Ratio
0
1
2
3
4
5
6
7
8
0
1
2
3
4
Distance From Crosslinked Surface (mm)

Fig. 21



5 Mrad, annealed 6 days
10 Mrad, annealed 6 days
15 Mrad, annealed 6 days
Oxidation Ratio
0
1
2
3
4
5
6
7
8
0
1
2
3
4
Distance From Crosslinked Surface (mm)

Fig. 22

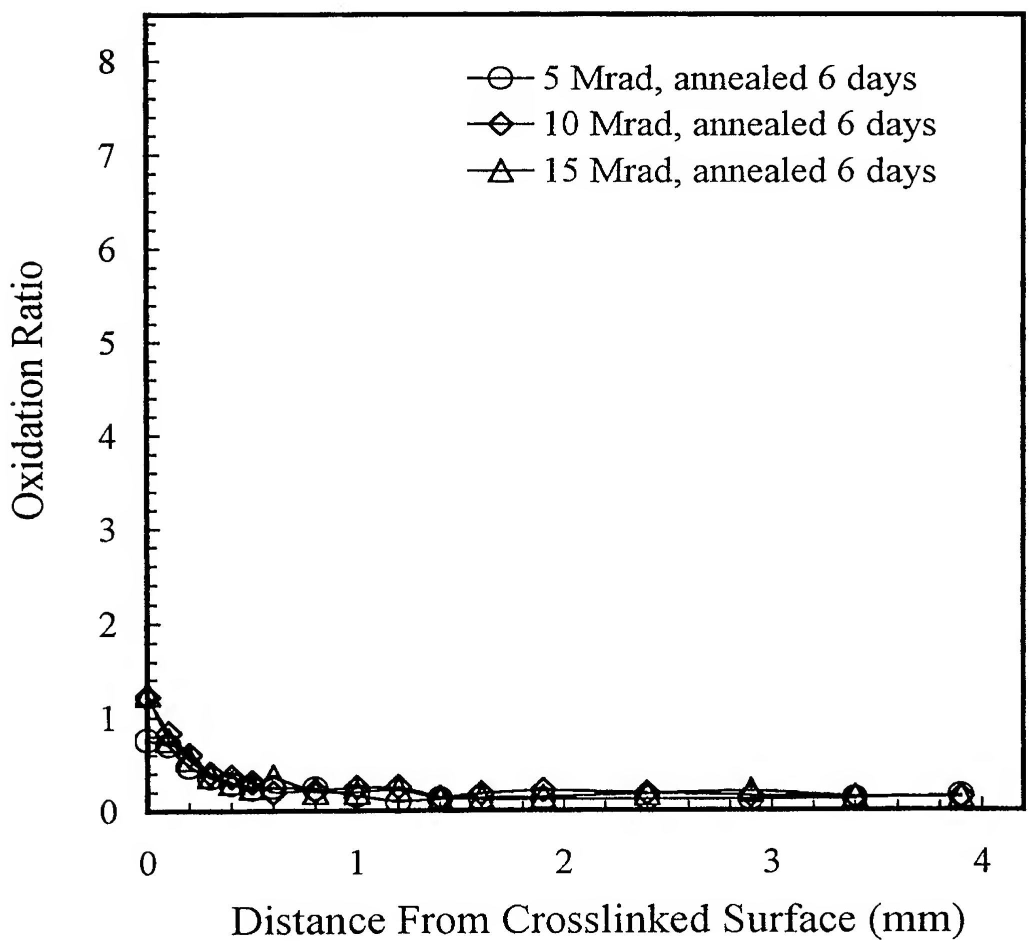

5 Mrad, annealed 6 days
10 Mrad, annealed 6 days
15 Mrad, annealed 6 days
Oxidation Ratio
0
1
2
3
4
5
6
7
8
0
1
2
3
4
Distance From Crosslinked Surface (mm)

Fig. 23

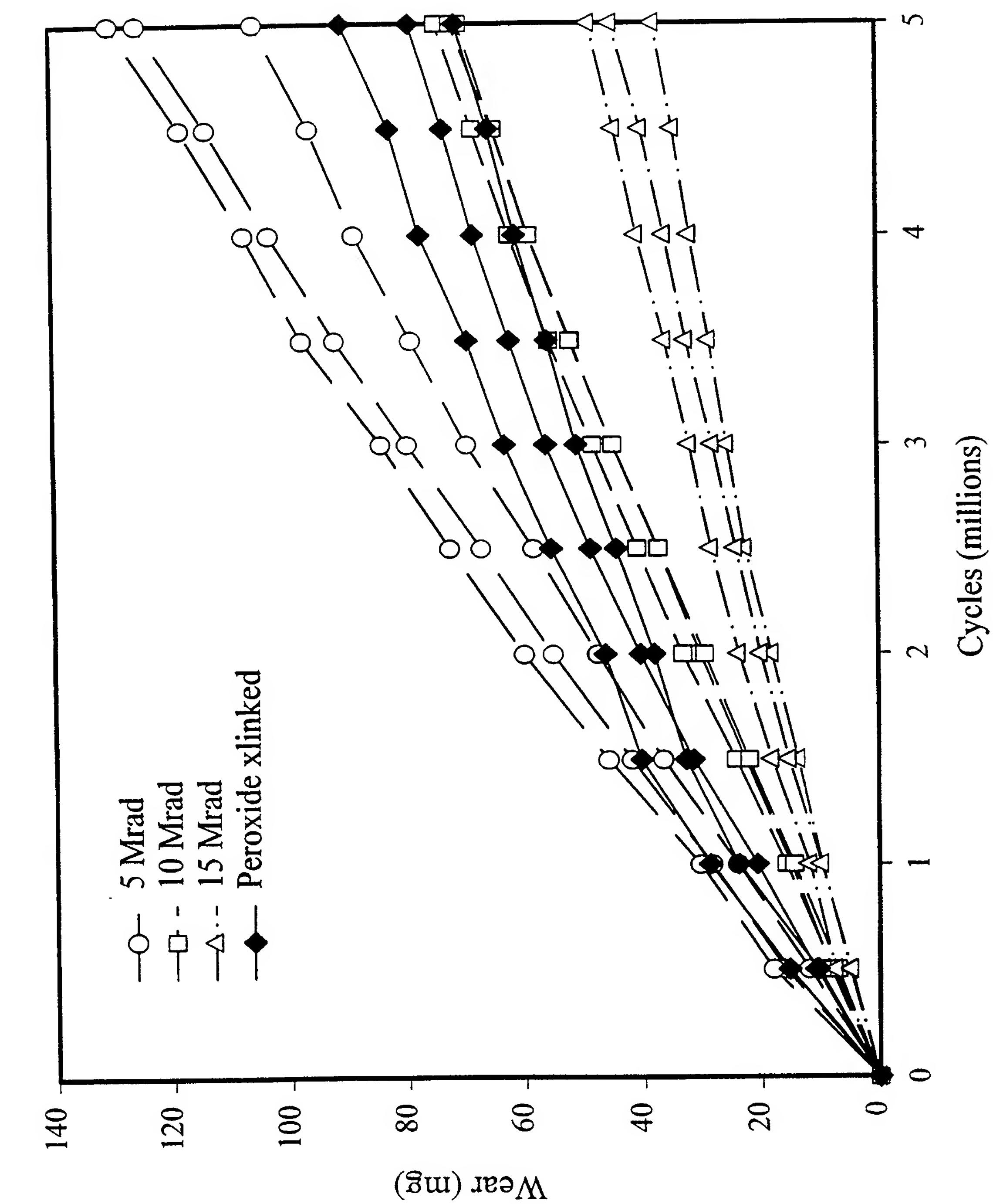
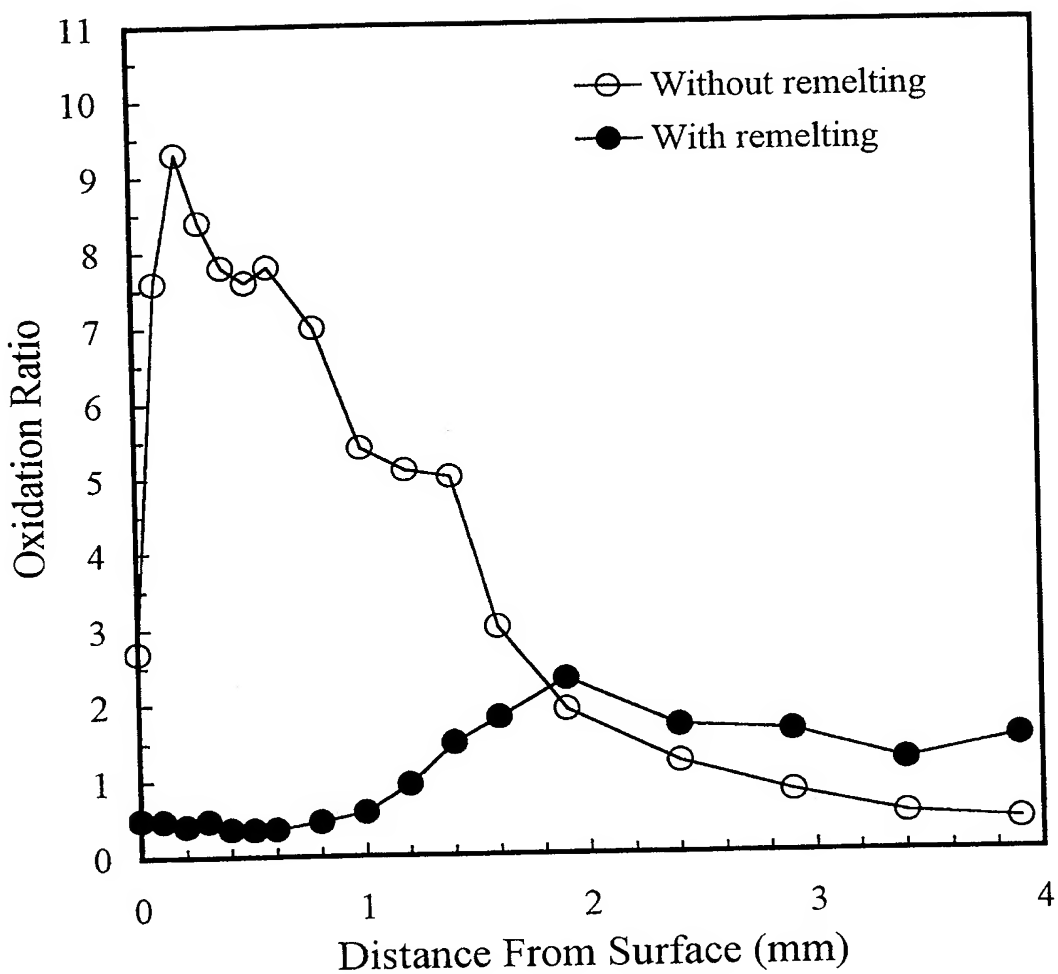

Wear (mg)
0
20
40
60
80
100
120
140
Cycles (millions)
0
1
2
3
4
5
5 Mrad
10 Mrad
15 Mrad
Peroxide xlinked

Fig. 24


Without remelting
With remelting
Oxidation Ratio
0
1
2
3
4
5
6
7
8
9
10
11
0
1
2
3
4
Distance From Surface (mm)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/08241

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :A61F 2/28
US CL :623/18
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 427/2.24, 551; 523/113, 115; 525/937; 623/16, 18, 20

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS, WEST
Sarch Terms: cross linking, irradiation, implant, bearing surface

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	WO 97/29793 A (MERRILL et al.) 21 August 1997, Example 3.	2, 3, 11, 12 --- 4, 9
X	EP 0 722 973 A (SALOVEY et al.) 24 July 1996, pages 4-6.	5-7
X --- Y	WO 98/01085 A (SHEN et al.) 15 January 1998, Figs. 15-18, and Step 3 on page 20.	1 --- 4, 9
X	WO 95/21212 A (FARRAR) 10 August 1995, page 7.	2
X, P	US 5,879,400 A (MERRILL et al.) 09 March 1999, col. 11 line 45 to col. 12 line 20.	2, 3, 11, 12

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

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Date of the actual completion of the international search
16 JUNE 1999

Date of mailing of the international search report
14 JUL 1999

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/08241

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,593,719 A (DEARNALEY et al.) 14 January 1997, col. 4 lines 5-63.	5